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INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2014

Impacts, Adaptation, and Vulnerability

Part A: Global and Sectoral Aspects

WG II

WORKING GROUP II CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

Climate Change 2014
Impacts, Adaptation, and Vulnerability
Part A: Global and Sectoral Aspects

Working Group II Contribution to the
Fifth Assessment Report of the
Intergovernmental Panel on Climate Change

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Planting of mangrove seedlings in Funafala, Funafuti Atoll, Tuvalu. © David J. Wilson

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Foreword, Preface, and Dedication

Foreword

Climate Change 2014: Impacts, Adaptation, and Vulnerability is the second volume of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) — *Climate Change 2013/2014* — and was prepared by its Working Group II. The volume focuses on why climate change matters and is organized into two parts, devoted respectively to human and natural systems and regional aspects, incorporating results from the reports of Working Groups I and III. The volume addresses impacts that have already occurred and risks of future impacts, especially the way those risks change with the amount of climate change that occurs and with investments in adaptation to climate changes that cannot be avoided. For both past and future impacts, a core focus of the assessment is characterizing knowledge about vulnerability, the characteristics and interactions that make some events devastating, while others pass with little notice.

Three elements are new in this assessment. Each contributes to a richer, more nuanced understanding of climate change in its real-world context. The first new element is a major expansion of the topics covered in the assessment. In moving from 20 chapters in the AR4 to 30 in the AR5, the Working Group II assessment makes it clear that expanding knowledge about climate change and its impacts mandates attention to more sectors, including sectors related to human security, livelihoods, and the oceans. The second new element is a pervasive focus on risk, where risk captures the combination of uncertain outcomes and something of value at stake. A framing based on risk provides a framework for utilizing information on the full range of possible outcomes, including not only most likely outcomes but also low probability but high consequence events. The third new element is solid grounding in the evidence that impacts of climate change typically involve a number of interacting factors, with climate change adding new dimensions and complications. The implication is that understanding the impacts of climate change requires a very broad perspective.

The IPCC was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988, with the mandate to provide the world community with the most up-to-date and comprehensive scientific, technical, and socio-economic information about climate change. The IPCC assessments have since then played a major role in motivating governments to adopt and implement policies in responding to climate change, including the United Nations Framework Convention on Climate Change and the Kyoto Protocol. IPCC's AR5 provides an important foundation of information for the world's policymakers, to help them respond to the challenge of climate change.

The *Impacts, Adaptation, and Vulnerability* report was made possible thanks to the commitment and voluntary labor of a large number of leading scientists. We would like to express our gratitude to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, and Reviewers. We would also like to thank the staff of the Working Group II Technical Support Unit and the IPCC Secretariat for their dedication in organizing the production of a very successful IPCC report. Furthermore, we would like to express our thanks to Dr. Rajendra K. Pachauri, Chairman of the IPCC, for his patient and constant guidance through the process, and to Drs. Vicente Barros and Chris Field, Co-Chairs of Working Group II, for their skillful leadership. We also wish to acknowledge and thank those governments and institutions that contributed to the IPCC Trust Fund and supported the participation of their resident scientists in the IPCC process. We would like to mention in particular the Government of the United States of America, which funded the Technical Support Unit; the Government of Japan, which hosted the plenary session for the approval of the report; and the Governments of Japan, United States of America, Argentina, and Slovenia, which hosted the drafting sessions to prepare the report.

M. Jarraud
Secretary-General
World Meteorological Organization

A. Steiner
Executive Director
United Nations Environment Programme

Preface

The Working Group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGII AR5) considers climate change impacts, adaptation, and vulnerability. It provides a comprehensive, up-to-date picture of the current state of knowledge and level of certainty, based on the available scientific, technical, and socio-economic literature. As with all IPCC products, the report is the result of an assessment process designed to highlight both big-picture messages and key details, to integrate knowledge from diverse disciplines, to evaluate the strength of evidence underlying findings, and to identify topics where understanding is incomplete. The focus of the assessment is providing information to support good decisions by stakeholders at all levels. The assessment is a unique source of background for decision support, while scrupulously avoiding advocacy for particular policy options.

Scope of the Report

Climate change impacts, adaptation, and vulnerability span a vast range of topics. With the deepening of knowledge about climate change, we see connections in expanding and diverse areas, activities, and assets at risk. Early research focused on direct impacts of temperature and rainfall on humans, crops, and wild plants and animals. New evidence points to the importance of understanding not only these direct impacts but also potential indirect impacts, including impacts that can be transmitted around the world through trade, travel, and security. As a consequence, few aspects of the human endeavor or of natural ecosystem processes are isolated from possible impacts in a changing climate. The interconnectedness of the Earth system makes it impossible to draw a confined boundary around climate change impacts, adaptation, and vulnerability. This report does not attempt to bound the issue. Instead, it focuses on core elements and identifies connecting points where the issue of climate change overlaps with or merges into other issues.

The integrative nature of the climate change issue underlies three major new elements of the WGII contribution to the AR5. The first is explicit coverage of a larger range of topics, with new chapters. Increasing knowledge, expressed in a rapidly growing corpus of published literature, enables deeper assessment in a number of areas. Some of these are geographic, especially the addition of two chapters on oceans. Other new chapters further develop topics covered in earlier assessments, reflecting the increased sophistication of the available research. Expanded coverage of human settlements, security, and livelihoods builds on new research concerning human dimensions of climate change. A large increase in the published literature on adaptation motivates assessment in a suite of chapters.

A second new emphasis is the focus on climate change as a challenge in managing and reducing risk, as well as capitalizing on opportunities. There are several advantages to understanding the risk of impacts from climate change as resulting from the overlap of hazards from the physical climate and the vulnerability and exposure of people, ecosystems, and assets. Some of the advantages accrue from the opportunity to evaluate factors that regulate each component of risk. Others relate to the way that a focus on risk can clarify bridges to solutions. A focus on risk can link historical experience with future projections. It helps integrate the role of extremes. And it highlights the importance of considering the full range of possible outcomes, while opening the door to a range of tools relevant to decision making under uncertainty.

A third new emphasis ties together the interconnectedness of climate change with a focus on risk. Risks of climate change unfold in environments with many interacting processes and stressors. Often, climate change acts mainly through adding new dimensions and complications to sometimes longstanding challenges. Appreciating the multi-stressor context of the risks of climate change can open doors to new insights and approaches for solutions.

Increased knowledge of the risks of climate change can be a starting point for understanding the opportunities for and implications of possible solutions. Some of the solution space is in the domain of mitigation, extensively covered by the Working Group III contribution to the AR5. The WGII AR5 delves deep into adaptation. But many opportunities exist in linking climate change adaptation, mitigation, and sustainable development. In contrast to past literature that tended to characterize adaptation, mitigation, and sustainable development as competing agendas, new literature identifies complementarities. It shines light on options for leveraging investments in managing and reducing the risks of climate change to enable vibrant communities, robust economies, and healthy ecosystems, in all parts of the world.

Structure of the Report

The Working Group II contribution to the IPCC Fifth Assessment Report consists of a brief summary for policymakers, a longer technical summary, and 30 thematic chapters, plus supporting annexes. A series of cross-chapter boxes and a collection of Frequently Asked Questions provide an integrated perspective on selected key issues. Electronic versions of all the printed contents, plus supplemental online material, are available at no charge at www.ipcc.ch.

The report is published in two parts. Part A covers global-scale topics for a wide range of sectors, covering physical, biological, and human systems. Part B considers the same topics, but from a regional perspective, exploring the issues that arise from the juxtaposition of climate change, environment, and available resources. Conceptually, there is some overlap between the material in Parts A and B, but the contrast in framing makes each part uniquely relevant to a particular group of stakeholders. For setting context and meeting the needs of users focused on regional-scale issues, Part B extracts selected materials from the Working Group I and Working Group III contributions to the Fifth Assessment Report. To acknowledge the different purposes for the two parts and the balanced contributions of the co-chairs, the listing order of the editors differs between the two parts, with Chris Field listed first on Part A and Vicente Barros listed first on Part B.

The 20 chapters in Part A are arranged in six thematic groups.

Context for the AR5

The two chapters in this group, (1) Point of departure and (2) Foundations for decision making, briefly summarize the conclusions of the Fourth Assessment Report and the Working Group I contribution to the AR5. They explain the motivation for the focus on climate change as a challenge in managing and reducing risks and assess the relevance of diverse approaches to decision making in the context of climate change.

Natural and Managed Resources and Systems, and Their Uses

The five chapters in this group, (3) Freshwater resources, (4) Terrestrial and inland water systems, (5) Coastal systems and low-lying areas, (6) Ocean systems, and (7) Food security and food production systems, cover diverse sectors, with a new emphasis on resource security. The ocean systems chapter, focused on the processes at work in ocean ecosystems, is a major element of the increased coverage of oceans in the WGII AR5.

Human Settlements, Industry, and Infrastructure

The three chapters in this group, (8) Urban areas, (9) Rural areas, and (10) Key economic sectors and services, provide expanded coverage of settlements and economic activity. With so many people living in and moving to cities, urban areas are increasingly important in understanding the climate change issue.

Human Health, Well-Being, and Security

The three chapters in this group, (11) Human health: impacts, adaptation, and co-benefits, (12) Human security, and (13) Livelihoods and poverty, increase the focus on people. These chapters address a wide range of processes, from vector-borne disease through conflict and migration. They assess the relevance of local and traditional knowledge.

Adaptation

An expanded treatment of adaptation is one of the signature changes in the WGII AR5. Chapters treat (14) Adaptation needs and options, (15) Adaption planning and implementation, (16) Adaptation opportunities, constraints, and limits, and (17) Economics of adaptation. This coverage reflects a large increase in literature and the emergence of climate-change adaptation plans in many countries and concrete action in some.

Multi-Sector Impacts, Risks, Vulnerabilities, and Opportunities

The three chapters in this group, (18) Detection and attribution of observed impacts, (19) Emergent risks and key vulnerabilities, and (20) Climate-resilient pathways: adaptation, mitigation, and sustainable development, collect material from the chapters in both Parts A and B to provide a sharp focus on aspects of climate change that emerge only by examining many examples across the regions of the Earth and the entirety of the human endeavor. These chapters provide an integrative view of three central questions related to understanding risks in a changing climate – what are the impacts to date (and how certain is the link to climate change), what are the most important risks looking forward, and what are the opportunities for linking responses to climate change with other societal goals.

The 10 chapters in Part B start with a chapter, (21) Regional context, structured to help readers understand and capitalize on regional information. It is followed by chapters on 9 world regions: (22) Africa, (23) Europe, (24) Asia, (25) Australasia, (26) North America, (27) Central and South America, (28) Polar regions, (29) Small islands, and (30) The ocean (taking a regional cut through ocean issues, including human utilization of ocean resources). Each chapter in this part is an all-in-one resource for regional stakeholders, while also contributing to and building from the global assessment. Regional climate-change maps, which complement the Working Group I Atlas of Global and Regional Climate Projections, and quantified key regional risks are highlights of these chapters. Each chapter explores the issues and themes that are most relevant in the region.

Process

The Working Group II contribution to the IPCC Fifth Assessment Report was prepared in accordance with the procedures of the IPCC. Chapter outlines were discussed and defined at a scoping meeting in Venice in July 2009, and outlines for the three Working Group contributions were approved at the 31st session of the Panel in November 2009, in Bali, Indonesia. Governments and IPCC observer organizations nominated experts for the author team. The team of 64 Coordinating Lead Authors, 179 Lead Authors, and 66 Review Editors was selected by the WGII Bureau and accepted by the IPCC Bureau in May 2010. More than 400 Contributing Authors, selected by the chapter author teams, contributed text.

Drafts prepared by the author teams were submitted for two rounds of formal review by experts, of which one was also a review by governments. Author teams revised the draft chapters after each round of review, with Review Editors working to assure that every review comment was fully considered, and where appropriate, chapters were adjusted to reflect points raised in the reviews. In addition, governments participated in a final round of review of the draft Summary for Policymakers. All of the chapter drafts, review comments, and author responses are available online via www.ipcc.ch. Across all of the drafts, the WGII contribution to the AR5 received 50,492 comments from 1,729 individual expert reviewers from 84 countries. The Summary for Policymakers was approved line-by-line by the Panel, and the underlying chapters were accepted at the 10th Session of IPCC Working Group II and the 38th Session of the IPCC Panel, meeting in Yokohama, Japan, from March 25-30, 2014.

Acknowledgments

For the AR5, Working Group II had an amazing author team. In many ways, the author team encompasses the entire scientific community, including scientists who conducted the research and wrote the research papers on which the assessment is based, and the reviewers who contributed their wisdom in more than 50,000 review comments. But the process really ran on the sophistication, wisdom, and dedication of the 309 individuals from 70 countries who comprise the WGII team of Coordinating Lead Authors, Lead Authors, and Review Editors. These individuals, with the support of a talented group of volunteer chapter scientists and the assistance of scores of contributing authors, demonstrated an inspirational commitment to scientific quality and public service. Tragically, three of our most experienced authors passed away while the report was being written. We greatly miss JoAnn Carmin, Abby Sallenger, and Steve Schneider.

We benefitted greatly from the advice and guidance of the Working Group II Bureau: Amjad Abdulla (Maldives), Eduardo Calvo Buendía (Peru), José M. Moreno (Spain), Nirivololona Raholijao (Madagascar), Sergey Semenov (Russian Federation), and Neville Smith (Australia). Their understanding of regional resources and concerns has been invaluable.

Throughout the AR5, we benefitted greatly from the wisdom and insight of our colleagues in the IPCC leadership, especially the IPCC chair, R.K. Pachauri. All of the members of the IPCC Executive Committee worked effectively and selflessly on issues related to the reports from all three working groups. We extend a heartfelt thanks to all of the members of the ExCom: R.K. Pachauri, Ottmar Edenhofer, Ismail El Gizouli, Taka Hiraishi, Thelma Krug, Hoesung Lee, Ramón Pichs Madruga, Qin Dahe, Youba Sokona, Thomas Stocker, and Jean-Pascal van Ypersele.

We are very appreciative of the enthusiastic cooperation of the nations that hosted our excellent working meetings, including four lead author meetings and the 10th Session of Working Group II. We gratefully acknowledge the support of the governments of Japan, the United States, Argentina, and Slovenia for hosting the lead author meetings, and the government of Japan for hosting the approval session. The government of the United States provided essential financial support for the Working Group II Technical Support Unit. Special thanks to the principals of the United States Global Change Research Program for orchestrating the funding across many research agencies.

We want very much to thank the staff of the IPCC Secretariat: Renate Christ, Gaetano Leone, Carlos Martin-Novella, Jonathan Lynn, Brenda Abrar-Milani, Jesbin Baidya, Laura Biagioni, Mary Jean Burer, Annie Courtin, Judith Ewa, Joelle Fernandez, Nina Peeva, Sophie Schlingemann, Amy Smith, and Werani Zabula. Thanks to Francis Hayes who served as conference officer for the approval session. Thanks to the individuals who coordinated the organization for each of the lead authors meetings. This was Mizue Yuzurihara and Claire Summers for LAM1, Sandy MacCracken for LAM2, Ramiro Saurral for LAM3, and Mojca Deželak for LAM4. Students from Japan, the United States, Argentina, and Slovenia helped with the lead author meetings.

The WGII Technical Support Unit was fabulous. They combined scientific sophistication, technical excellence, artistic vision, deep resilience, and profound dedication, not to mention a marked ability to compensate for oversights by and deficiencies of the co-chairs. Dave Dokken, Mike Mastrandrea, Katie Mach, Kris Ebi, Monalisa Chatterjee, Sandy MacCracken, Eric Kissel, Yuka Estrada, Leslie White, Eren Bilir, Rob Genova, Beti Girma, Andrew Levy, and Patricia Mastrandrea have all made wonderful contributions to the report. In addition, the work of David Ropeik (frequently asked questions), Marcos Senet (assistant to Vicente Barros), Terry Kornak (technical edits), Marilyn Anderson (index), Liu Yingjie (Chinese author support), and Janak Pathak (UNEP communications) made a big difference. Kyle Terran, Gete Bond, and Sandi Fikes facilitated travel. Volunteer contributions from John Kelley and Ambarish Malpani greatly enhanced reference management. Catherine Lemmi, Ian Sparkman, and Danielle Olivera were super interns.

We extend a deep, personal thanks to our families and to the families of every author and reviewer. We know you tolerated many late nights and weekends with partners, parents, or children sitting at the computer or mumbling about one more assignment from us.

Vicente Barros
IPCC WGII Co-Chair

Chris Field
IPCC WGII Co-Chair

Dedication

Credit: Odd-Steinar Tøllefsen

Yuri Antonievich Izrael
(15 May 1930 to 23 January 2014)

The Working Group II contribution to the IPCC Fifth Assessment Report is dedicated to the memory of Professor Yuri Antonievich Izrael, first Chair of Working Group II from 1988 to 1992 and IPCC Vice Chair from 1992 to 2008. Professor Izrael was a pioneer, opening doors that have allowed thousands of scientists to contribute to the work of the IPCC.

Through a long and distinguished career, Professor Izrael was a strong proponent of environmental sciences, meteorology, climatology, and international organizations, especially the IPCC and the World Meteorological Organization. A creative researcher and tireless institution builder, Dr. Izrael founded and for more than two decades led the Institute of Global Climate and Ecology.

In the IPCC, Professor Izrael played a central role in creating the balance of IPCC efforts on careful observations, mechanisms, and systematic projections using scenarios. An outspoken advocate for the robust integration of scientific excellence and broad participation in IPCC reports, Dr. Izrael pioneered many of the features that assure the comprehensiveness and integrity of IPCC reports.

Summary for Policymakers

Cross-Chapter Boxes

CR

Coral Reefs

Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection, and appealing environments for tourism (Wild et al., 2011). About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011), including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling), and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (Section 29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; Sections 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5), and more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment, and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (Sections 5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see Section 6.3.1. for physiological details and Section 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; Sections 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5, and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997–1998 was unmatched in the period 1903–1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; Sections 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; Section 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs toward net dissolution (*medium confidence*; Section 5.4.2.4).

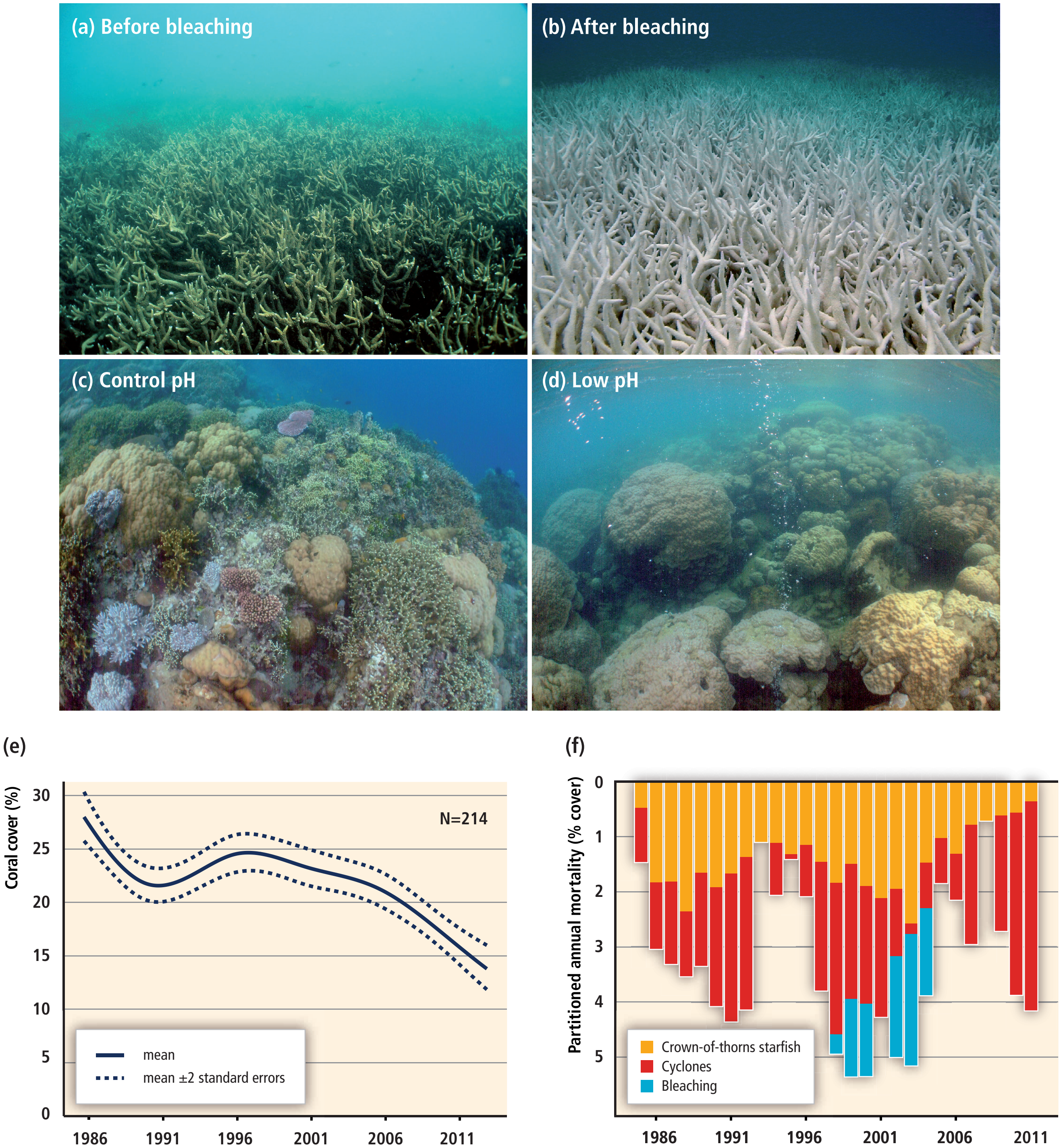

Figure CR-1 | (a, b) The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Approximately 95% of the coral community was severely bleached in 2002 (Elvidge et al., 2004). Corals experience increasing mortality as the intensity of a heating event increases. A few coral species show the ability to shuffle symbiotic communities of dinoflagellates and appear to be more tolerant of warmer conditions (Berkelmans and van Oppen, 2006; Jones et al., 2008). (c, d) Three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius et al., 2011), including reduced coral diversity (–39%), severely reduced structural complexity (–67%), lower density of young corals (–66%), and fewer crustose coralline algae (–85%). At high CO_2 sites (d; median pH_T ~7.8, where pH_T is pH on the total scale), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (c; median pH_T ~8.0). Reef development ceases at pH_T values below 7.7. (e) Temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N=number of reefs, De'ath et al., 2012). (f) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). (Photo credit: R. Berkelmans (a and b) and K. Fabricius (c and d).)

Ocean warming and acidification have synergistic effects in several reef-builders (Section 5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; Section 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg et al., 2007). The abundance of reef building corals is in rapid decline in many Pacific and Southeast Asian regions (*very high confidence*, 1 to 2% per year for 1968–2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by more than 80% on many Caribbean reefs (1977–2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators, and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones et al., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate–related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the Representative Concentration Pathway (RCP)3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present-day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high-frequency bleaching through 2100 (*limited evidence*, *limited agreement*; Logan et al., 2014). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and de Leiva Moreno, 2003). More than half (55%) of the 49 island countries considered by Newton et al. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Bell et al., 2013).
- *Coastal protection*: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification, and higher rates of dissolution and bioerosion due to ocean warming and acidification (Sections 5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the global gross domestic product (GDP) but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001–2011; Laurans et al., 2013). At the local scale, these two services provided in 2009–2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour et al., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig et al., 2012), suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012; Billé et al., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm et al., 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod et al., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2013) and coastal pollutants enriched with fertilizers can increase acidification (Kelly et al., 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; Section 5.2.4.4, 30.5).

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EA

Ecosystem-Based Approaches to Adaptation—Emerging Opportunities

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Ecosystem-based adaptation (EBA), defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009), integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see IPCC AR5 WGII Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even serve as a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls, and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches (CBD, 2009). In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012, Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:
- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and

enhanced baseflows, flood regulation and protection services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Opperman et al., 2009; Midgley et al., 2012)

- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques.
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach (CBD, 2009). The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

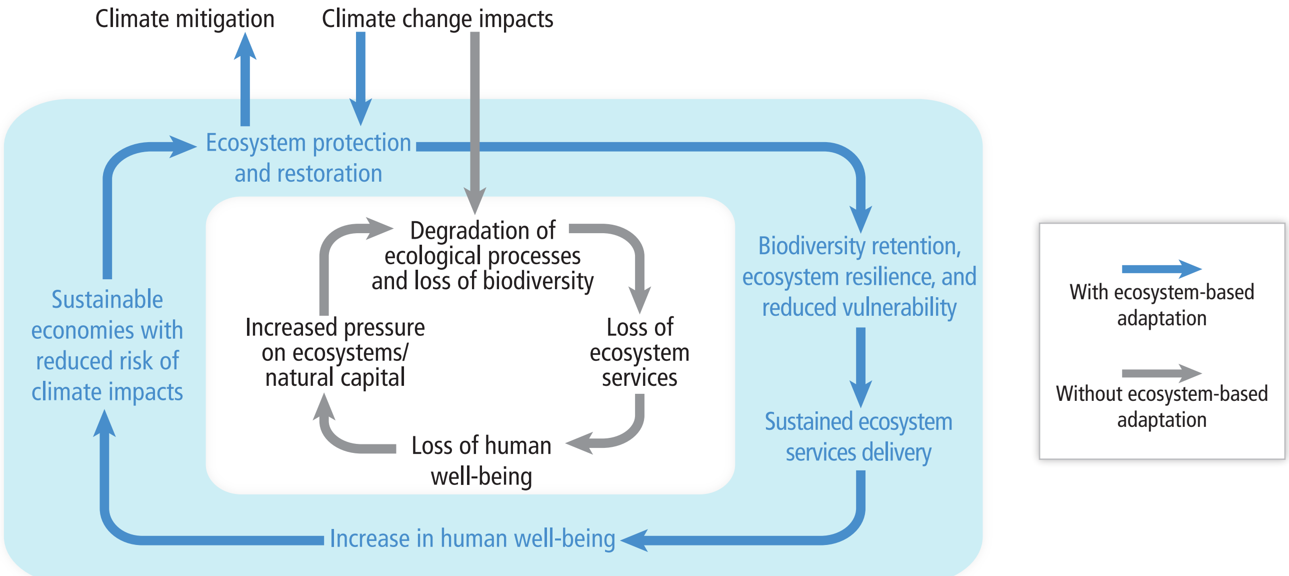

Figure EA-1 | Adapted from Munang et al. (2013). Ecosystem-based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

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GC

Gender and Climate Change

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Gender, along with sociodemographic factors of age, wealth, and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation, and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger et al., 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer et al., 2007; Buechler, 2009; Nelson and Stathers, 2009; Nightingale, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Omolo, 2011; Resureccion, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health, and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labor markets, making women in particular less able to cope with and adapt to climate change impacts (Paavola, 2008; Djoudi and Brockhaus, 2011; Rijkers and Costa, 2012). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whereas both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; Section 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity because food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota et al., 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger et al., 2007). Additional literature published since that time adds nuances by showing how socially constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*; Section 11.3.3, Table 12-3). Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981 and 2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007; see also Box 13-1). Reasons for gendered differences in mortality include various socially and culturally determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house, even during floods and in risk-prone areas (Bradshaw, 2010). Although the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality (Box 13-1). In Hai Lang district, Vietnam, for example, more men died than women as a result of their involvement in search and rescue and protection of fields during flooding (Campbell et al., 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the USA and Australia (Jenkins and Phillips, 2008; Anastario et al., 2009; Alston, 2011; Whittenbury, 2013; see also Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (Section 11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and São Paulo (Bell et al., 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Vincent et al., 2010; Arora-Jonsson, 2011; Figueiredo and Perkins, 2012). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women because cash generation is seen as a male activity in rural areas (Gladwin et al., 2001; see also Section 13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor, which women cannot necessarily afford to provide (Baiphethi et al., 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Goulden et al., 2009; Vincent et al., 2010; Below et al., 2012) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert and Machado, 2012; Bee et al., 2013; Tschakert, 2013; see also Section 22.4.3 and Table 22-5).

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HS

Heat Stress and Heat Waves

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According to WGI, it is *very likely* that the number and intensity of hot days have increased markedly in the last three decades and *virtually certain* that this increase will continue into the late 21st century. In addition, it is *likely* (*medium confidence*) that the occurrence of heat waves (multiple days of hot weather in a row) has more than doubled in some locations, but *very likely* that there will be more frequent heat waves over most land areas after mid-century. Under a medium warming scenario, Coumou et al. (2013) predicted that the number of monthly heat records will be more than 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +7°C or more, the habitability of parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and may act as triggers of tipping points (Hughes et al., 2013). Consequently, heat stress plays an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society (Chapters 10, 11, 12, 13)

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present-day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012; see also Section 8.2.3.1). In low- and medium-income countries, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health (Chapter 11)

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro et al., 2011; Nitschke et al., 2011; Rahmstorf and Coumou, 2011; Diboulo et al., 2012; Hansen et al., 2012). Elderly people and people with circulatory and respiratory diseases are also vulnerable even in developed countries; they can become victims even inside their own houses (Honda et al., 2011). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, et al., 2008). High temperatures are also associated with an increase in air-borne allergens acting as triggers for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems (Chapters 4, 5, 6, 30)

Tree mortality is increasing globally (Williams et al., 2013) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult owing to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013; see also Box 4.2).

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (*medium confidence*; Hoegh-Guldberg et al., 2007; see also Figure 6-5; Sections 6.3.1, 6.3.5, 30.4, 30.5; CC-MB).

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*; Sections 5, 6, 30.4, 30.5, CC-CR, CC-MB).

Agriculture (Chapter 7)

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2013). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and suitability for crops (*medium evidence*, *medium agreement*; Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the USA, current economic losses due to heat stress of livestock are estimated at several billion US$ annually (St-Pierre et al., 2003).

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KR

A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

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The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development context (e.g., in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. A representative set of lines of sight is provided from across WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.

Table KR-1 | Examples of hazards/stressors, key vulnerabilities, key risks, and emergent risks.

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Terrestrial and Inland Water Systems (Chapter 4)	Rising air, soil, and water temperature (Sections 4.2.4, 4.3.2, 4.3.3)	Exceedance of eco-physiological climate tolerance limits of species (limited coping and adaptive capacities), increased viability of alien organisms	Risk of loss of native biodiversity, increase in non-native organism dominance	Cascades of native species loss due to interdependencies
		Health response to spread of temperature-sensitive vectors (insects)	Risk of novel and/or much more severe pest and pathogen outbreaks	Interactions among pests, drought, and fire can lead to new risks and large negative impacts on ecosystems.
	Change in seasonality of rain (Section 4.3.3)	Increasing susceptibility of plants and ecosystem services, due to mismatch between plant life strategy and growth opportunities	Changes in plant functional type mix leading to biome change with respective risks for ecosystems and ecosystem services	Fire-promoting grasses grow in winter-rainfall areas and provide fuel in dry summers.
Ocean Systems (Chapter 6)	Rising water temperature, increase of (thermal and haline) stratification, and marine acidification (Section 6.1.1)	Tolerance limits of endemic species surpassed (limited coping and adaptive capacities), increased abundance of invasive organisms, high susceptibility and sensitivity of warm water coral reefs and respective ecosystem services for coastal communities (Sections 6.3.1, 6.4.1)	Risk of loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms. Increasing risk of loss of coral cover and associated ecosystem with reduction of biodiversity and ecosystem services (Section 6.3.1)	Enhancement of risk as a result of interactions, e.g., acidification and warming on calcareous organisms (Section 6.3.5)
		New vulnerabilities can emerge as a result of shifted productivity zones and species distribution ranges, largely from low to high latitudes (Sections 6.3.4, 6.5.1), shifting fishery catch potential with species migration (Sections 6.3.1, 6.5.2, 6.5.3)	Risks due to unknown productivity and services of new ecosystem types (Sections 6.4.1, 6.5.3)	Enhancement of risk due to interactions of warming, hypoxia, acidification, new biotic interactions (Sections 6.3.5, 6.3.6)
	Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication (Section 6.1.1)	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates (Section 6.3.3)	Risk of loss of larger animals and plants, shifts to hypoxia-adapted, largely microbial communities with reduced biodiversity (Section 6.3.3)	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans (Section 6.3.5)
	Enhanced harmful algal blooms in coastal areas due to rising water temperature (Section 6.4.2.3)	Increasing susceptibility and limited adaptive capacities of important ecosystems and valuable services due to already existing multiple stresses (Sections 6.3.5, 6.4.1)	Increasing risk due to enhanced frequency of dinoflagellate blooms and respective potential losses and degradations of coastal ecosystems and ecosystem services (Section 6.4.2)	Disproportionate enhancement of risk due to interactions of various stresses (Section 6.3.5)
Food Security and Food Production Systems (Chapter 7)	Rising average temperatures and more frequent extreme temperatures (Sections 7.1, 7.2, 7.4, 7.5)	Susceptibility of all elements of the food system from production to consumption, particularly for key grain crops	Risk of crop failures, breakdown of food distribution and storage processes	Increase in the global population to about 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt
	Extreme precipitation and droughts (Section 7.4)	Crops, pasture, and husbandry are susceptible and sensitive to drought and extreme precipitation.	Risk of crop failure, risk of limited food access and quality	Flood and droughts affect crop yields and quality, and directly affect food access in most developing countries. (Section 7.4)
Urban Areas (Chapter 8)	Inland flooding (Sections 8.2.3, 8.2.4)	Large numbers of people exposed in urban areas to flood events. Particularly susceptible are people in low-income informal settlements with inadequate infrastructure (and often on flood plains or along river banks). These bring serious environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and widespread impermeable surfaces. Local governments are often unable or unwilling to give attention to needed flood-related disaster risk reduction. Much of the urban population unable to get or afford housing that protects against flooding, or insurance. Certain groups are more sensitive to ill health from flood impacts, which may include increased mosquito- and water-borne diseases.	Risks of deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	In many urban areas, larger and more frequent flooding impacting much larger population. No insurance available or impacts reaching the limits of insurance. Shift in the burden of risk management from the state to those at risk, leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
	Coastal flooding (including sea level rise and storm surge) (Sections 8.1.4, 8.2.3, 8.2.4)	High concentrations of people, businesses, and physical assets including critical infrastructure exposed in low-lying and unprotected coastal zones. Particularly susceptible is the urban population that is unable to get or afford housing that protects against flooding or insurance. The local government is unable or unwilling to give needed attention to disaster risk reduction.	Risks from deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	Additional 2 billion or so urban dwellers expected over the next three decades Sea level rise means increasing risks over time, yet with high and often increasing concentrations of population and economic activities on the coasts. No insurance available or reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps

Continued next page →

Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Urban Areas (continued) (Chapter 8)	Heat and cold (including urban heat island effect) (Section 8.2.3)	Particularly susceptible is a large and often increasing urban population of infants, young children, older age groups, expectant mothers, people with chronic diseases or compromised immune system in settlements exposed to higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency, and social services to adapt to new risk levels and set up needed initiatives for vulnerable groups	Risk of mortality and morbidity increasing, including shifts in seasonal patterns and concentrations due to hot days with higher or more prolonged high temperatures or unexpected cold spells. Avoiding risks often most difficult for low-income groups	Duration and variability of heat waves increasing risks over time for most locations owing to interactions with multiple stressors such as air pollution
	Water shortages and drought in urban regions (Sections 8.2.3, 8.2.4)	Lack of piped water to homes of hundreds of millions of urban dwellers. Many urban areas subject to water shortages and irregular supplies, with constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural–urban linkages. Dependence on water resources in energy production systems	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban ecology and its services including urban and peri-urban agriculture.	Cities' viability may be threatened by loss or depletion of freshwater sources—including for cities dependent on distant glacier melt water or on depleting groundwater resources.
	Changes in urban meteorological regimes lead to enhanced air pollution. (Section 8.2.3)	Increases in exposure and in pollution levels with impacts most serious among physiologically susceptible populations. Limited coping and adaptive capacities, due to lacking implementation of pollution control legislation of urban governments	Increasing risk of mortality and morbidity, lowered quality of life. These risks can also undermine the competitiveness of global cities to attract key workers and investment.	Complex and compounding health crises
	Geo-hydrological hazards (salt water intrusion, mud/land slides, subsidence) (Sections 8.2.3, 8.2.4)	Local structures and networked infrastructure (piped water, sanitation, drainage, communications, transport, electricity, gas) particularly susceptible. Inability of many low-income households to move to housing on safer sites.	Risk of damage to networked infrastructure. Risk of loss of human life and property	Potential for large local and aggregate impacts Knock-on effects for urban activities and well-being
	Wind storms with higher intensity (Sections 8.1.4, 8.2.4)	Substandard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retrofit buildings and infrastructure in cities Local government unable or unwilling to give attention to disaster risk reduction (limited coping and adaptive capacities)	Risk of damage to dwellings, businesses, and public infrastructure. Risk of loss of function and services. Challenges to recovery, especially where insurance is absent	Challenges to individuals, businesses, and public agencies where the costs of retrofitting are high and other sectors or interests capture investment budgets; potential for tensions between development and risk reduction investments
	Changing hazard profile including novel hazards and new multi-hazard complexes (Sections 8.1.4, 8.2.4)	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks (e.g., geophysical rather than hydrometeorological)	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications. Potential of psychological shock from unanticipated risks	Loss of faith in risk management institutions. Potential for extreme impacts that are magnified by a lack of preparation and capacity in response
	Compound slow-onset hazards including rising temperatures and variability in temperature and water (Sections 8.2.2, 8.2.4)	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture are especially susceptible.	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture, and other productive or protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision, and disaster risk reduction
	Climate change–induced or intensified hazard of more diseases and exposure to disease vectors (Sections 8.2.3, 8.2.4)	Large urban population that is exposed to food-borne and water-borne diseases and to malaria, dengue, and other vector-borne diseases that are influenced by climate change	Risk due to increases in exposure to these diseases	Lack of capacity of public health system to simultaneously address these health risks with other climate-related risks such as flooding
Rural Areas (Chapter 9)	Drought in pastoral areas (Sections 9.3.3.1, 9.3.5.2)	Increasing vulnerability due to encroachment on pastoral rangelands, inappropriate land policy, misperception and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice	Risk of famine Risk of loss of revenues from livestock trade	Increasing risks for rural livelihoods through animal disease in pastoral areas combined with direct impacts of drought
	Effects of climate change on artisanal fisheries (Sections 9.3.3.1, 9.3.5.2)	Artisanal fisheries affected by pollution and mangrove loss, competition from aquaculture, and the neglect of the sector by governments and researchers as well as complex property rights	Risk of economic losses for artisanal fisherfolk, due to declining catches and incomes and damage to fishing gear and infrastructure	Reduced dietary protein for those consuming artisanally caught fish, combined with other climate-related risks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Rural Areas (continued) (Chapter 9)	Water shortages and drought in rural areas (Section 9.3.5.1.1)	Rural people lacking access to drinking and irrigation water. High dependence of rural people on natural resource-related activities. Lack of capacity and resilience in water management regimes (institutionally driven). Increased water demand from population pressure	Risk of reduced agricultural productivity of rural people, including those dependent on rainfed or irrigated agriculture, or high-yield varieties, forestry, and inland fisheries. Risk of food insecurity and decrease in incomes. Decreases in household nutritional status (Section 9.3.5.1)	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand, water used by non-food crops), including potential conflicts for access to water. Water-related diseases
Human Health (Chapter 11)	Increasing frequency and intensity of extreme heat	Older people living in cities are most susceptible to hot days and heat waves, as well as people with preexisting health conditions. (Section 11.3)	Risk of increased mortality and morbidity during hot days and heat waves. (Section 11.4.1) Risk of mortality, morbidity, and productivity loss, particularly among manual workers in hot climates	The number of elderly people is projected to triple from 2010 to 2050. This can result in overloading of health and emergency services.
	Increasing temperatures, increased variability in precipitation	Poorer populations are particularly susceptible to climate-induced reductions in local crop yields. Food insecurity may lead to undernutrition. Children are particularly vulnerable. (Section 11.3)	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and morbidity from undernutrition may slow or reverse. (Section 11.6.1)	Combined effects of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequality, and ongoing food insecurity for the poor
	Increasing temperatures, changing patterns of precipitation	Non-immune populations who are exposed to water- and vector-borne diseases that are sensitive to meteorological conditions (Section 11.3)	Increasing health risks due to changing spatial and temporal distribution of diseases strains public health systems, especially if this occurs in combination with economic downturn. (Section 11.5.1)	Rapid climate and other environmental change may promote emergence of new pathogens.
	Increased variability in precipitation	People exposed to diarrhea aggravated by higher temperatures, and unusually high or low precipitation (Section 11.3)	Risk that the progress to date in reducing childhood deaths from diarrheal disease is compromised (Section 11.5.2)	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhea risk
Livelihoods and Poverty (Chapter 13)	Increasing frequency and severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall (Sections 13.2.1.2, 13.2.1.4, 13.2.2.2)	Poorly endowed farmers (high and persistent poverty), particularly in drylands, are susceptible to these hazards, since they have a very limited ability to compensate for losses in water-dependent farming systems and/or livestock.	Risk of irreversible harm due to short time for recovery between droughts, approaching tipping point in rainfed farming system and/or pastoralism	Deteriorating livelihoods stuck in poverty traps, heightened food insecurity, decreased land productivity, outmigration, and new urban poor in LICs and MICs
	Floods and flash floods in informal urban settlements and mountain environments, destroying physical assets (e.g., homes, roads, terraces, irrigation canals) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4)	High exposure and susceptibility of people, particularly children and elderly, as well as disabled in flood-prone areas. Inadequate infrastructure, culturally imposed gender roles, and limited ability to cope and adapt due to political and institutional marginalization and high poverty adds to the susceptibility of these people in informal urban settlements; limited political interest in development and building adaptive capacity	Risk of high morbidity and mortality due to floods and flash floods. Factors that further increase risk may include a shift from transient to chronic poverty due to eroded human and economic assets (e.g., labor market) and economic losses due to infrastructure damage.	Exacerbated inequality between better-endowed households able to invest in flood-control measures and/or insurance and increasingly vulnerable populations prone to eviction, erosion of livelihoods, and outmigration
	Increased variability of precipitation; shifts in mean climate and extreme events (Sections 13.2.1.1, 13.2.1.4)	Limited ability to cope owing to exhaustion of social networks, especially among the elderly and female-headed households; mobilization of labor and food no longer possible	Hazard combines with vulnerability to shift populations from transient to chronic poverty due to persistent and irreversible socioeconomic and political marginalization. In addition, the lack of governmental support, as well as limited effectiveness of response options, increase the risk.	Increasing yet invisible multidimensional vulnerability and deprivation at the convergence of climatic hazards and socioeconomic stressors
	Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising water demand (Sections 13.2.1.1, 13.2.1.5)	Rural communities are particularly susceptible, due to the marginalization of rural water users to the benefit of urban users, given political and economic priorities (e.g., Australia, Andes, Himalayas, Caribbean).	Risk of loss of rural livelihoods, severe economic losses in agriculture, and damage to cultural values and identity; mental health impacts (including increased rates of suicide)	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of new poverty in MICs and HICs
	Sea level rise (Sections 13.1.4, 13.2.1.1, 13.2.2.1, 13.2.2.3)	High number of people exposed in low-lying areas coupled with high susceptibility due to multidimensional poverty, limited alternative livelihood options among poor households, and exclusion from institutional decision-making structures	Risk of severe harm and loss of livelihoods. Potential loss of common-pool resources; of sense of place, belonging, and identity, especially among indigenous populations	Loss of livelihoods and mental health risks due to radical change in landscape, disappearance of natural resources, and potential relocation; increased migration
	Increasing temperatures and heat waves (Sections 13.2.1.5, 13.2.2.3, 13.2.2.4)	Agricultural wage laborers, small-scale farmers in areas with multidimensional poverty and economic marginalization, children in urban slums, and the elderly are particularly susceptible.	Risk of increased morbidity and mortality due to heat stress, among male and female workers, children, and the elderly, limited protection due to socioeconomic discrimination and inadequate governmental responses	Declining labor pool for agriculture coupled with new challenges for rural health care systems in LICs and MICs; aging and low-income populations without safety nets in HICs at risk

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Livelihoods and Poverty (continued) (Chapter 13)	Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4, 13.2.1.5)	People highly dependent on rainfed agriculture are particularly at risk. Persistent poverty among subsistence farmers and urban wage laborers who are net buyers of food with limited coping mechanisms	Risk of crop failure, spikes in food prices, reduction in consumption to protect household assets, risk of food insecurity, shifts from transient to chronic poverty due to limited ability to reduce risks	Food riots, child food poverty, global food crises, limits of insurance and other risk-spreading strategies
	Changing rainfall patterns (temporally and spatially)	Households or people with a high dependence on rainfed agriculture and little access to alternative modes of income	Risks of crop failure, food shortage, severe famine	Coincidence of hazard with periods of high global food prices leads to risk of failure of coping strategies and adaptation mechanisms such as crop insurance (risk spreading).
	Stressor from soaring demand (and prices) for biofuel feedstocks due to climate policies	Farmers and groups that have unclear and/or insecure land tenure arrangements are exposed to the dispossession of land due to land grabbing in developing countries.	Risk of harm and loss of livelihoods for some rural residents due to soaring demand for biofuel feedstocks and insecure land tenure and land grabbing	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production
	Increasing frequency of extreme events (droughts, floods), e.g., if 1:20 year drought/flood becomes 1:5 year drought/flood	Pastoralists and small farmers subject to damage to their productive assets (e.g., herds of livestock; dykes, fences, terraces)	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent Risks and Key Vulnerabilities (Chapter 19)	Warming and drying (precipitation changes of uncertain magnitude) (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; sociocultural constraints on some adaptation options (Sections 19.2.2, 19.3.2.2, 19.6.1.1, 19.6.3.4)	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. (Sections 19.3.2.2, 19.6.3.4)	Competition for water from diverse sectors (e.g., energy, agriculture, industry) interacts with climate changes to produce locally severe shortages. (Sections 19.3.2.2, 19.6.3.4)
	Changes in regional and seasonal temperature and precipitation over land (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Communities highly dependent on ecosystem services (Sections 19.2.2.1, 19.3.2.1) which are negatively affected by changes in regional and seasonal temperature	Risk of large-scale species richness loss over most of the global land surface. 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are expected to lose ≥50% of their current climatic range by the 2080s leading to loss of services. (Section 19.3.2.1)	Widespread loss of ecosystem services, including: provisioning, such as food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefit (Sections 19.3.2.1, 19.6.3.4)
Africa (Chapter 22)	Increasing temperature	Children, pregnant women, and those with compromised health status are particularly at risk for temperature-related changes in diarrheal and vector-borne diseases, and for temperature-related reductions in crop yields. Outdoor workers, older adults, and young children are most susceptible to hot weather and heat waves. (Sections 22.3.5.2, 22.3.5.4)	Risk of changes in the geographic distribution, seasonality, and incidence of infectious diseases, leading to increases in the health burden. Risk of increased burdens of stunting in children. Risk of increase in morbidity and mortality during hot days and heat waves	Interactions among factors lead to emerging and re-emerging epidemics.
		Populations dependent on aquatic systems and aquatic ecosystem services that are sensitive to increased water temperatures	Loss of aquatic ecosystems and risks for people who might depend on these resources; reduction in freshwater fisheries production (Sections 22.3.2.2, 22.3.4.4)	Risk of loss of livelihoods due to interactions of loss of ecosystem services and other climate-related stressors on poor communities
		Rural and urban populations whose food and livelihood security is diminished	Risk of harm and loss due to increased heat stress on crops and livestock resulting in reduced productivity; increased food storage losses due to spoilage (Sections 22.3.4.1, 22.3.4.2)	Range expansion of crop pests and diseases to high-elevation agroecosystems (Section 22.3.4.3)
	Extreme events, e.g., floods and flash floods (and drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk (Sections 22.3.6, 22.4.3)	Increasing risk of mortality, harm and losses due to water logging triggered by heavy rainfall events	Compounded risk of epidemics including diarrheal diseases (e.g., cholera)
		Susceptible groups include those who experience diminished access to food resulting from reduced capacity to transport, store, and market food, such as the urban poor.	Risk of food shortages and of damages to the food system due to storms and flooding	Food price spikes due to convergence of climatic and non-climatic forces that reduce food access for the poor whose income is disproportionately spent on food (Section 22.3.4.5)
		Children, pregnant women, and those with compromised health status are particularly vulnerable to reduced access to safe water and improved sanitation and increasing food insecurity. (Sections 22.3.5.2, 22.3.5.3)	Risk of crop and livestock losses from drought Risk of reduced water supply and quality for household use. (Sections 22.3.4.1, 22.3.4.2) Risk of increased incidence of food- and water-borne diseases (e.g., cholera) and undernutrition. Risk of drinking water contamination due to heavy precipitation events and flooding (Section 22.3.5.2)	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children (Section 22.3.5.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Europe (Chapter 23)	Extreme weather events (Section 23.9)	Sectors with limited coping and adaptive capacity as well as high sensitivity to these extreme events, such as transport, energy, and health, are particularly susceptible.	Risk of new systemic threats due to stress on multiple and interconnected sectors. Risk of failure of service provision of one or more sectors	Disproportionate intensification of risk due to increasing interdependencies
	Climate change increases the spatial distribution and seasonality of pests and diseases. (Section 23.4.1, 23.4.3, 23.4.4)	High susceptibility of plants and animals that are exposed to pests and diseases	Risk of increases in crop losses and animal diseases or even fatalities of livestock	Increasing risks due to limited response options and various feedback processes in agriculture, e.g., use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors
	Extreme weather events and reduced water availability due to climate change (Section 23.3.4)	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions.	Increasing risk of power shortages due to limited energy supply, e.g., of nuclear power plants due to limited cooling water during heat stress	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g., during a heat wave.
Asia (Chapter 24)	Rising average temperatures and more frequent extreme temperatures, as well as changing rainfall patterns (temporally and spatially)	Food systems and food production systems for key grain crops, particularly rice and other cereal crop farming systems, are highly susceptible. (Section 24.4.4.3)	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. (Section 24.4.4.3)	Increase in Asian population combined with rising temperatures affecting food production. Upper temperature limit to the ability of some food systems to adapt could be reached.
	Rising sea level	Paddy fields and farmers near the coasts are particularly susceptible. (Section 24.4.4.3)	Risk of loss of arable areas due to submergence (Section 24.4.4.3)	Migration of farming communities to higher elevation areas entails risks for migrants and receiving regions.
	Projected increase in frequency of various extreme events (heat wave, floods, and droughts) and sea level rise	Increasing exposure due to convergence of livelihood and properties into coastal megacities. People in areas that are not sufficiently protected against natural hazards are particularly susceptible.	Risk of loss of life and assets due to coastal floods accompanied by increasing vulnerabilities.	Projected increase in disruptions of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities
Australasia (Chapter 25)	Rising air and sea surface temperatures, drying trends, reduced snow cover, increased intensity of severe cyclones, ocean acidification (Section 25.2; Table 25-1; Figure 25-4; WGI AR5 Chapter 14 and Atlas)	Species that live in a limited climatic range and that suffer from habitat fragmentation as well as from external stressors (pollution, runoff, fishing, tourism, introduced predators, and pests) are especially susceptible. (Sections 25.6.1, 25.6.2)	Risk of significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (Sections 25.6.1, 25.6.2, 25.10.2)	Increasing risk from compound extreme events across time and space, and cumulative adaptation needs, with recovery and risk reduction measures hampered further by impacts and responses reaching across different levels of government (Sections 25.10.2, 25.10.3; Box 25-9)
	Increased extreme rainfall related to flood risk in many locations (Section 25.2; Table 25-1)	Adaptation deficit of existing infrastructure and settlements to current flood risk; expansion and densification of urban areas; effective adaptation includes transformative changes such as land-use controls and retreat. (Sections 25.3, 25.10.2; Box 25-8)	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (Box 25-8; Section 25.10.2)	
	Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios (Section 25.2; Box 25-1; WGI AR5 Chapter 13)	Long-lived and high asset value coastal infrastructure and low-lying ecosystems are highly susceptible. Expansion of coastal populations and assets into coastal zones increases the exposure. Conflicting priorities constrain adaptation options and limit effective response strategies. (25.3, Box 25-1)	Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages toward the upper end of projected ranges (Box 25-1; Sections 25.6.1, 25.6.2, 25.10.2)	
North America (Chapter 26)	Increases in frequency and/or intensity of extreme events, such as heavy precipitation, river and coastal floods, heat waves, and droughts (Sections 26.2.2, 26.3.1, 26.8.1)	Physical infrastructure in a declining state in urban areas particularly susceptible. Also increases in income disparities and limited institutional capacities might result in larger proportions of people susceptible to these stressors due to limited economic resources. (Sections 26.7, 26.8.2)	Risk of harm and loss in urban areas, particularly in coastal and dry environments due to enhanced vulnerabilities of social groups, physical systems, and institutional settings combined with the increases of extreme weather events (Section 26.8.1)	Inability to reduce vulnerability in many areas results in an increase in risk more so than change in physical hazard. (Section 26.8.3)
	Higher temperatures, decreases in runoff, and lower soil moisture due to climate change (Sections 26.2, 26.3)	Vulnerability of small rural landholders, particularly in Mexican agriculture, and of the poor in rural settlements (Sections 26.5, 26.8.2.2)	Risk of increased losses and decreases in agricultural production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena (Sections 26.5, 26.8.2.2)	Increasing risks of social instability and local economic disruption due to internal migration (Sections 26.2.1, 26.8.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
North America (continued) (Chapter 26)	Wildfires and drought conditions (Box 26-2)	Indigenous groups, low-income residents in peri-urban areas, and forest systems (Box 26-2; Section 26.8.2)	Risk of loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (Box 26-2; Section 26.8.3)	
	Extreme storm and heat events, air pollution, pollen, and infectious diseases (Section 26.6.1)	Susceptibility of individuals is determined by factors such as economic status, preexisting illness, age, and access to assets. (Section 26.6.1)	Increasing risk of extreme temperature-, storm-, pollen-, and infectious diseases–related human morbidity or mortality (Section 26.6.2)	
	River and coastal floods, and sea level rise (Sections 26.2.2, 26.4.2, 26.8.1)	Increasing exposure of populations, property, as well as ecosystems, partly resulting from overwhelmed drainage networks. Groups and economic sectors that highly depend on the functioning of different supply chains, public health institutions that can be disrupted, and groups that have limited coping capacities to deal with supply chain interruptions and disruptions to their livelihoods are particularly susceptible. (Sections 26.7, 26.8.1)	Risk of property damage, supply chain disruption, public health, water quality impairment, ecosystem disruption, infrastructure damage, and social system disruption from urban flooding due to river and coastal floods and floods of drainage networks (Sections 26.4.2, 26.8.1)	Multiple risks from interacting hazards on populations' livelihoods, infrastructure, and services (Sections 26.7, 26.8.3)
Central and South America (Chapter 27)	Reduced water availability in semi-arid regions and regions dependent on glacier meltwater; flooding in urban areas due to extreme precipitation (Sections 27.2.1, 27.3.3)	Groups that cannot keep agricultural livelihoods and are forced to migrate are especially vulnerable. Limited infrastructure and planning capacity can further increase the lack of coping and adaptive capacities to rapid changes expected (precipitation), especially in large cities.	Risk of loss of human lives, livelihood, and property	Increase in infectious diseases. Economic impacts due to reallocation of populations
	Ocean acidification and warming (Section 27.3.3; Box CC-OA)	Sensitivity of coral reef systems to ocean acidification and warming	Risk of loss of biodiversity (species) and risk of a reduced fishing capacity with respective impacts for coastal livelihoods	Economic losses and impact on food (fishery) production in certain regions
	Extremes of drought/ precipitation (Sections 27.2.1, 27.3.4)	Elevated CO_2 decreases nutrient contents in plants, especially nitrogen in relation to carbon in food products.	Risk of loss of (food) production and productivity in some regions where extreme events may occur. Need to adjust diet due to decrease in food quality (e.g., less protein due to lower nitrogen assimilation). Decrease in bioenergy production	Strong economic impacts related to the need to move crops to more suitable regions. Teleconnections (related to food quality) related to the intense exportation of food by the region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
	Higher temperatures and humidity lead to a spread of vector-borne diseases in altitude and latitude. (Section 27.3.7)	People exposed and vulnerable to vector-borne diseases and an increase in mosquito biting rates that increase the probability of human infections	Risk of increase in morbidity and in disability-adjusted life years (DALYs); risk of loss of human lives; risk of decrease in school and labor productivity	High economic impacts owing to the necessity to increase the financing of health programs, as well as the costs of DALYs, increase in hospitals and medical infrastructure adequate to cope with increasing disease incidence rates, and the spread of diseases to newer regions
Polar Regions (Chapter 28)	Loss of multi-year ice and reductions in the spatial extent of summer sea ice (Sections 28.2.5, 28.3.2, 28.4.1)	Indigenous communities that depend on sea ice for traditional livelihoods are vulnerable to this hazard, particularly due to loss of breeding and foraging platforms for marine mammals.	Risk of loss of traditional livelihoods and food sources.	Top-down shifts in food webs
		Ecosystems are vulnerable owing to the shifts in the distribution and timing of ice algal and ocean phytoplankton blooms.	Risk of disruption of synchronized timing of zooplankton ontogeny and availability of prey. Increased variability in secondary production while zooplankton adapt to shifts in timing. Risks also to local marine food webs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling
	Ocean acidification (Sections 28.2.2, 28.3.2)	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioral properties during larval development	Localized loss of endemic species, local impacts on marine food webs	Localized declines in commercial fisheries. Local declines in fish, shellfish, seabirds, and marine mammals
	Shifts in boundaries of marine eco-regions due to rising water temperature, shifts in mixed layer depth, changes in the distribution and intensity of ocean currents (Sections 28.2.2, 28.3.2)	Marine organisms that are susceptible to spatial shifts are particularly vulnerable.	Risk of changes in the structure and function of marine systems and potentially species invasions	Disputes over international fisheries and shared stocks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Polar Regions (continued) (Chapter 28)	Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather (Sections 28.1, 28.4.1)	Many traditional subsistence food sources—especially for indigenous peoples—such as Arctic marine and land mammals, fish, and waterfowl. Various traditional livelihoods are susceptible to these hazards.	Risk of loss of habitats and changes in migration patterns of marine species	Enhancement of risk to food security and basic nutrition—especially for indigenous peoples—from loss of subsistence foods and increased risk to subsistence hunters', herders', and fishers' health and safety in changing ice conditions
	Increased river and coastal flooding and erosion and thawing of permafrost (Sections 28.2.4, 28.3.1, 28.3.4)	Rural and remote communities as well as urban communities in low-lying Arctic areas are exposed. Susceptibility and limited coping capacity of community water supplies due to potential damages to infrastructure.	Community and public health infrastructure damaged resulting in disease from contamination and sea water intrusion	Reduced water quality and quantity may result in increased rates of infection, other medical problems, and hospitalizations.
	Extreme and rapidly changing weather, intense weather and precipitation events, rapid snow and ice melt, changing river and sea ice conditions, permafrost thaw (Section 28.2.4)	People living from subsistence travel and hunting, herding, and fishing, for example indigenous peoples in remote and isolated communities, are particularly susceptible.	Accidents, physical/mental injuries, death, and cold-related exposure, injuries, and diseases	Enhanced risks to safe travel or subsistence hunting, herding, fishing activities affect livelihoods and well-being.
	Diminished sea ice; earlier sea ice melt-out; faster sea ice retreat; thinner, less predictable ice in general; greater variability in snow melt/freeze; ice, weather, winds, temperatures, precipitation (Sections 28.2.5, 28.2.6, 28.4.1)	Livelihoods of many indigenous peoples (e.g., Inuit and Saami) depend upon subsistence hunting and access to and favorable conditions for animals. These livelihoods are susceptible. Also marine ecosystems are susceptible (e.g., marine mammals).	Risk of loss of livelihoods and damage due to, e.g., more difficult access to marine mammals associated with diminishing sea ice (a risk to the Inuit), and loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow" (a risk to the Saami).	Enhanced risk of loss of livelihoods and culture of increasing numbers of indigenous peoples, exacerbated by increasing loss of lands and sea ice for hunting, herding, fishing due to enhanced petroleum and mineral exploration, and increased maritime traffic
Small Islands (Chapter 29)	Increases in intensity of tropical cyclones (WGI AR5 Sections 14.6, 14.8.4)	Various countries and communities are vulnerable to these hazards because of their high dependence on natural and ecological systems for security of settlements and tourism (Section 29.3.3.1), human health (Section 29.3.3.2), and water resources (Section 29.3.2).	Risk of loss of ecosystems, settlements, and infrastructure, as well as negative impacts on human health and island economies (Figure 29-4)	Increased risk of interactions of damages to ecosystems, settlements, island economies, and risks to human life (Section 29.6; Figure 29-4)
	Ocean warming and acidification leading to coral bleaching (Sections 29.3.1.2, 30.5.4.2, 30.5.6.1.1, 30.5.6.2)	Tropical island communities are highly dependent on coral reef ecosystems for subsistence life styles, food security, coastal protection and beach, and reef-based tourist economic activity, and hence are highly susceptible to the hazard of coral bleaching. (Sections 29.3.1.2, 30.6.2.1.2)	Risk of decline and possible loss of coral reef ecosystems through thermal stress. Risk of serious harm and loss of subsistence lifestyles. Risk of loss of coastal protection and beaches, risk of loss of tourist revenue (Sections 29.3.1.1, 29.3.1.2)	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration/urbanization (Section 29.3.3.3; Chapter 9)
	Sea level rise (Sections 29.3.1.1, 30.3.1.2; WGI AR5 Section 3.7.1)	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also vulnerable to increasing inundation, erosion and wave incursion. (Sections 5.3.2, 29.3.1.1; Figure 29-2)	Risk of loss and harm due to sea level rise in small island communities. Global mean sea level is likely to increase by 0.35 to 0.70 m for Representative Concentration Pathway (RCP) 4.5 during the 21st century, threatening low-lying coastal areas and atoll islands. (Section 29.4.3, Table 29-1; WGI AR5 Section 13.5.1, Table 13.5)	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges. These events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. (Sections 29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1)

Continued next page →

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
The Ocean (Chapter 30)	Increasing ocean temperatures. Increased frequency of thermal extremes	Corals and other organisms whose tolerance limits are exceeded are particularly susceptible (especially CBS, STG, SES, and EUS ocean regions). (Sections 6.2.2.1, 6.2.2.2, 30.5.2, 30.5.4, 30.5.5; Boxes CC-CR, 30.5.6, CC-OA)	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism, and coastal protection (Sections 6.3.2. 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2, 30.5.2, 30.5.3, 30.5.4, 30.5.5; Box CC-CR)	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection (Sections 7.2.1.2, 30.6.2.1, 30.6.5)
		Marine species and ecosystems as well as fisheries and coastal livelihoods and tourism that cannot cope or adapt to changing temperatures and changes in the distribution are particularly vulnerable, especially for HLSBS, CBS, STG, and EBUE. (Sections 6.3.2, 6.3.4, 7.3.2.6, 30.5; Box CC-BIO)	Risk for fishery and coastal livelihoods. Fishery opportunity changes as stock abundance may rise or fall; increased risk of disease and invading species impacting ecosystems and fisheries (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.6, 7.4.2, 29.5.3, 29.5.4)	Significant risk of fishery collapse may develop as the capacity of fisheries to resist the following is exceeded: a) fundamental change to fishery composition, and b) the increased migration of disease and other organisms. (Sections 6.5.3, 7.5.1.1.3)
		Coastal ecosystems and communities that might be exposed to phenomena of elevated rates of microbial respiration leading to reduced oxygen at depth and increased spread of dead zones are particularly vulnerable (particularly for EBUE, SES, EUS).	Risk of loss of habitats and fishery resources as well as losses of key fisheries species. Oxygen levels decrease, leading to impacts on ecosystems (e.g., loss of habitat) and organisms (e.g., physiological performance of fish) resulting in reduced capture of key fisheries species.	Increasing risk of loss of livelihoods
		Deep sea life is sensitive to hazards and to change given the very constant conditions under which it has evolved. (30.1.3.1.3, 30.5.2, 30.5.5)	Risk of fundamental changes in conditions associated with deep sea (e.g., oxygen, pH, carbonate, CO_2, temperature) drive fundamental changes that result in broad-scale changes throughout the ocean. (Sections 30.1.3.1.3, 30.5.2, 30.5.5; Boxes CC-UP, CC-NPP)	Changes in the deep ocean may be a prelude to ocean wide changes with planetary implications.
	Rising ocean acidification	Reef systems, corals, and coastal ecosystems that are exposed to a reduced rate of calcification and greater decalcification leading to potential loss of carbonate reef systems, corals, molluscs, and other calcifiers in key regions, such as the CBS, STG (Section 6.2.2.2)	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture (Sections 6.2.5.3, 7.2.1.2, 7.3.2, 7.4.2,)	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. (Sections 7.5.1.1.3, 30.6)
		Marine organisms that are susceptible to changes in pH and carbonate chemistry imply a large number of changes to the physiology and ecology of marine organisms (particularly in CBS, STG, SES regions). (Sections 6.2.5, 6.3.4, 30.3.2.2)	Risk of fundamental shifts in ecosystems composition as well as organism function occur, leading to broad scale and fundamental change. Income and livelihoods from dependent communities are affected as ecosystem goods and services decline, with the prospect that recovery may take tens of thousands of years. (Section 6.1.1.2)	Risk to ecosystems and livelihoods is increased by the potential for interaction among ocean warming and acidification to create unknown impacts. (Section CC-OA)
		Coastal systems are increasingly exposed to upwelling in some areas, which results in periods of high CO_2, low O_2 and pH. (Box CC-UP; Sections 6.2.2.2, 6.2.5.3)	Risk of loss and harm to fishery and aquaculture operations and respective livelihoods (e.g., oyster cultivation), especially those exposed periodically to harmful conditions during elevated upwelling, which trigger adaptation responses. (Section 30.6.2.1.4)	Background pH and carbonate chemistry are also such that harmful conditions are always present (avoiding impacts via adaptation not possible any more). (Section 30.6.2.1.4)
	Increased stratification as a result of ocean warming; reduced ventilation	Ocean ecosystems are vulnerable due to the reduced regeneration of nutrients as mixing between the ocean and its surface is reduced (EUS, STG, and EBUE). (Sections 6.2, 6.3, 6.5, 30.5.2, 30.5.4, 30.5.5)	Risk of productivity losses of oceans and respective negative impacts on fisheries. The concentration of inorganic nutrients in the upper layers of the ocean is reduced, leading to lower rates of primary productivity. (Box CC-NPP)	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods (Section 6.4.1.1; Box CC-NPP)
		Ecosystems and organisms that are sensitive to decreasing oxygen levels (Sections 30.5.2, 30.5.3, 30.5.5, 30.5.6, 30.5.7)	Increased risk of dead (hypoxic) zones reducing key ecosystems and fisheries habitat (Sections 6.1.1.3, 30.3.2.3)	
	Changes to wind, wave height, and storm intensity	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. (Section 30.6.2)	Risk of increasing losses and damages to shipping and industrial infrastructure	Risk of accidents increases for enterprises such as shipping, as well as deep sea oil gas and mineral extraction.

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; EUS = Equatorial Upwelling Systems; HIC, LIC, MIC = high-, low-, and medium-income countries; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Sub-Tropical Gyres.

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MB

Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

Elvira Poloczanska (Australia), Ove Hoegh-Guldberg (Australia), William Cheung (Canada), Hans-Otto Pörtner (Germany), Michael T. Burrows (UK)

IPCC WGII AR4 presented the detection of a global fingerprint on natural systems and its attribution to climate change (AR4, Chapter 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected biological changes within the ocean to climate change (Section 6.3; Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change–mediated biological responses across ocean regions (*robust evidence*, *high agreement*, *high confidence*; Sections 6.2, 30.5; Table 6-7).

Poloczanska et al. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses (n = 1735) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the change in a biological parameter (including distribution, phenology, abundance, demography, or community composition) and, if change occurred, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) authors included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term climate variability.

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (Section 6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of 4.4 ± 0.7 days per decade (mean ± SE) and summer events by 4.4 ± 1.1 days per decade (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes, and seabirds (Sections 6.3.2, 30.5).

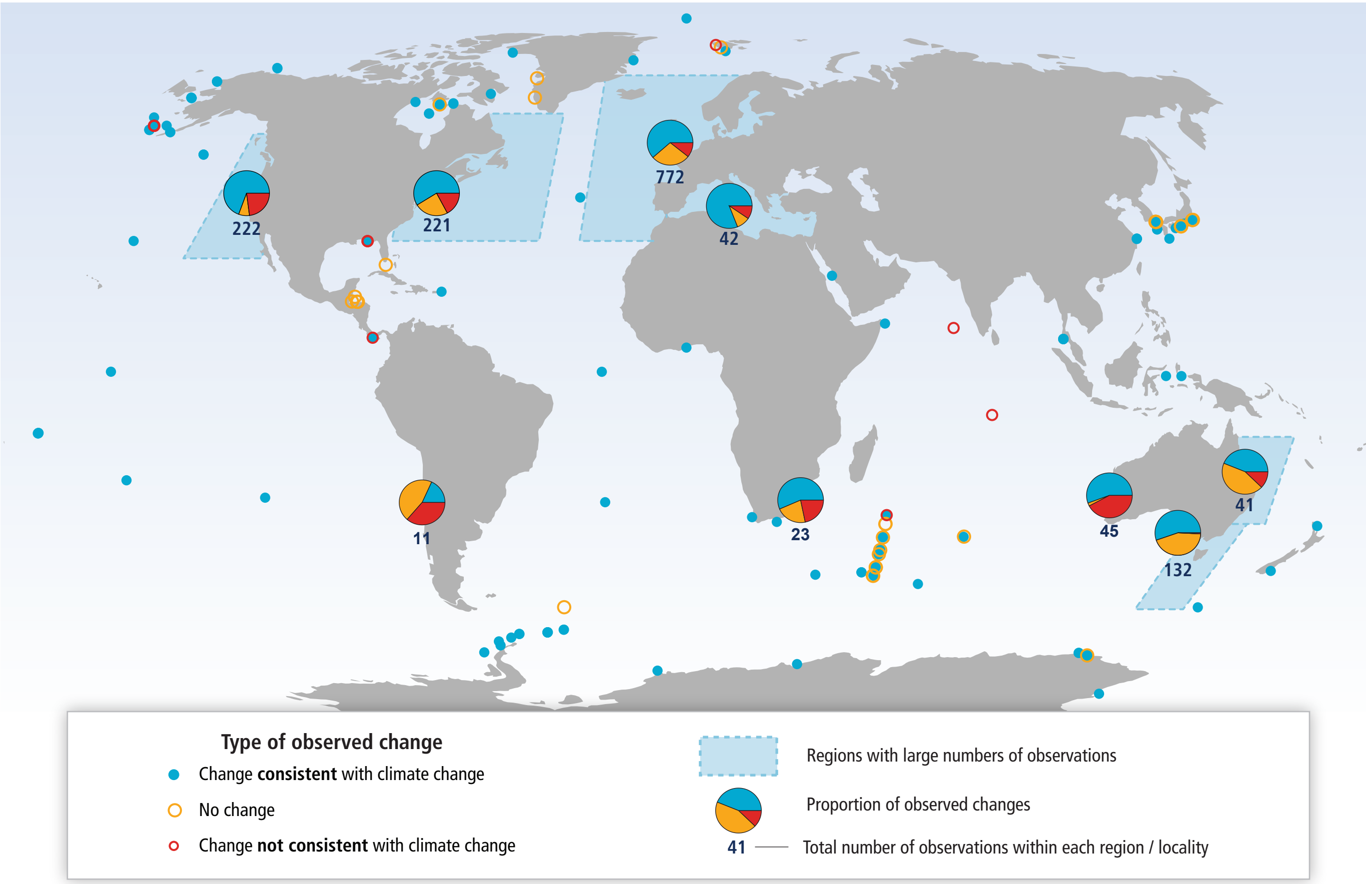

Figure MB-1 | 1735 observed responses to climate change from 208 single- and multi-species studies. Data shown include changes that are attributed (at least partly) to climate change (blue), changes that are inconsistent with climate change (red), and no change (orange). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distributions that surround an island or peninsula. Studies encompass areas from single sites (e.g., seabird breeding colony) to large ocean regions (e.g., continuous plankton recorder surveys in north-east Atlantic). For regions (indicated by blue shading) and localities with large numbers of observations, pie charts summarize the relative proportions of the three types of observed changes (consistent with climate change, inconsistent with climate change, and no change) in those regions or localities. The numbers indicate the total observations within each region or locality. Note: 57% of the studies included were published since AR4. (From Poloczanska et al., 2013).

The distributions of benthic, pelagic, and demersal species and communities have shifted by up to a thousand kilometers, although the range shifts have not been uniform across taxonomic groups or ocean regions (Sections 6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km per decade and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km per decade (Figure MB-2), revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4-6) despite slower warming of the ocean than land surface (WGI Section 3.2).

Poleward distribution shifts have resulted in increased species richness in mid- to high-latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson et al., 2011; see also Section 28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid- to high-latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1; Section 30.5). Observed changes in species composition of catches from 1970–2006 that are partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in subtropical and higher latitude regions, and reduction in abundance of subtropical species in equatorial waters (Cheung et al., 2013), with implications for fisheries (Sections 6.5, 7.4.2, 30.6.2.1).

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the ocean's surface (Section 30.3.1.1; Burrows et al., 2011). Pinsky et al. (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968–2011. Poloczanska et al. (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately the 1950s, have generally been able to track observed velocities (Figure MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities observed over most of the ocean surface, but with considerable variability within and among taxonomic groups (Poloczanska et al., 2013).

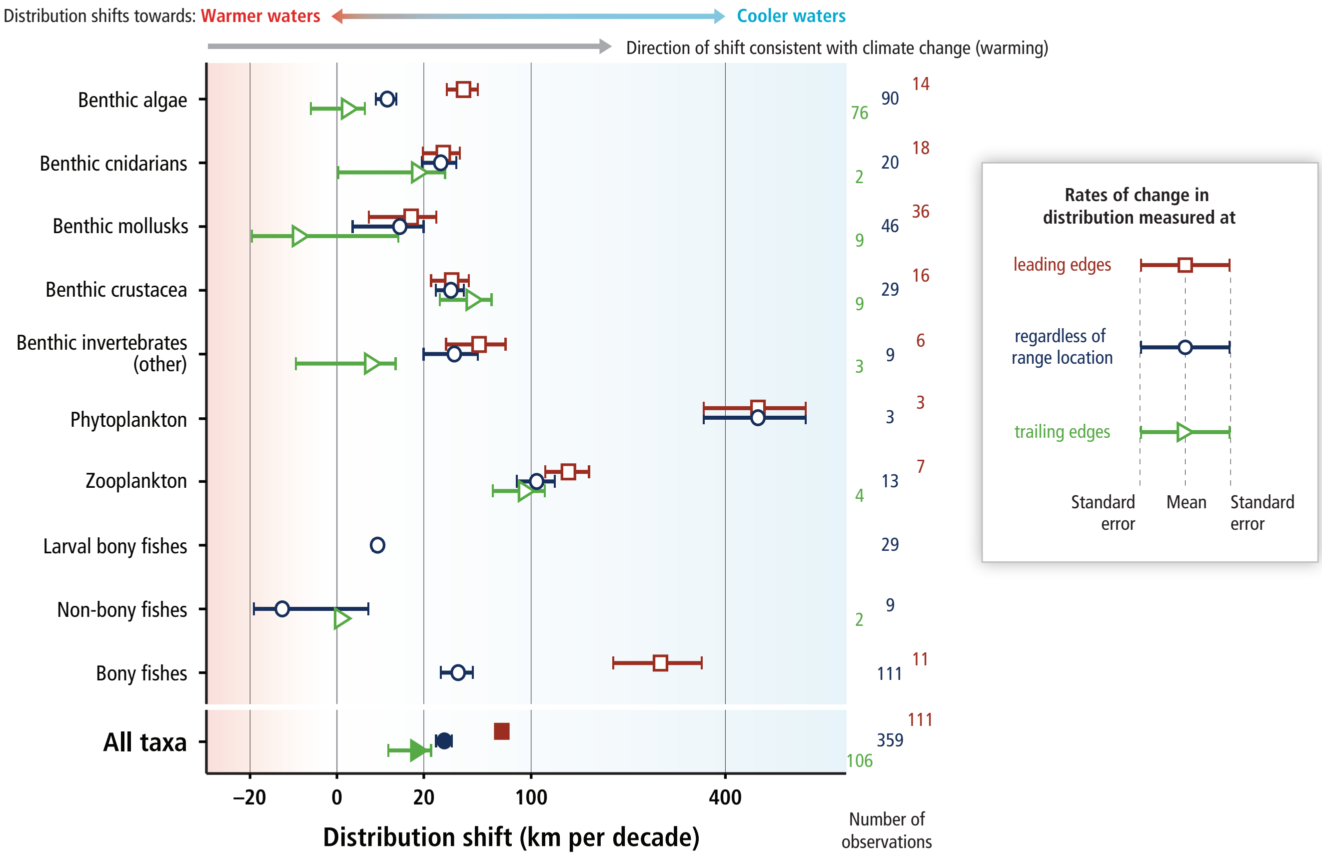

Figure MB-2 | Rates of change in distribution (kilometers per decade) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (green). Average distribution shifts were calculated using all data, regardless of range location, and are in dark blue. Distribution shifts have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations. Non-bony fishes include sharks, rays, lampreys, and hagfish. (From Poloczanska et al., 2013).

Biogeographic shifts are also influenced by other factors such as currents, nutrient and stratification changes, light levels, sea ice, species' interactions, habitat availability and fishing, some of which can be independently influenced by climate change (Section 6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., (Lima et al., 2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram et al., 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart et al., 2011).

Whether marine species can continue to keep pace as rates of warming, hence climate velocities, increase (Figure MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (Section 4.3.2.5; Figure 4-6). For marine species, the observed rates of shift are generally much faster than those for land species, particularly for primary producers and lower trophic levels (Poloczanska et al., 2013). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the Northeast Atlantic (Section 30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner et al., 2004; Perry et al., 2005; Simpson et al., 2011) as a consequence of the width of species-specific thermal windows and associated vulnerabilities (Figure 6-5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6-7A). Such effects may underlie abundance losses or local extinctions, "regime shifts" between coexisting species, or critical mismatches between predator and prey organisms, resulting in changes in local and regional species richness, abundance, community composition, productivity, energy flows, and invasion resistance. Even among Antarctic stenotherms, differences in biological responses related to mode of life, phylogeny and associated metabolic capacities exist (Section 6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society as well as facilitate adaptive management strategies formitigating these impacts (Sections 6.3, 6.4).

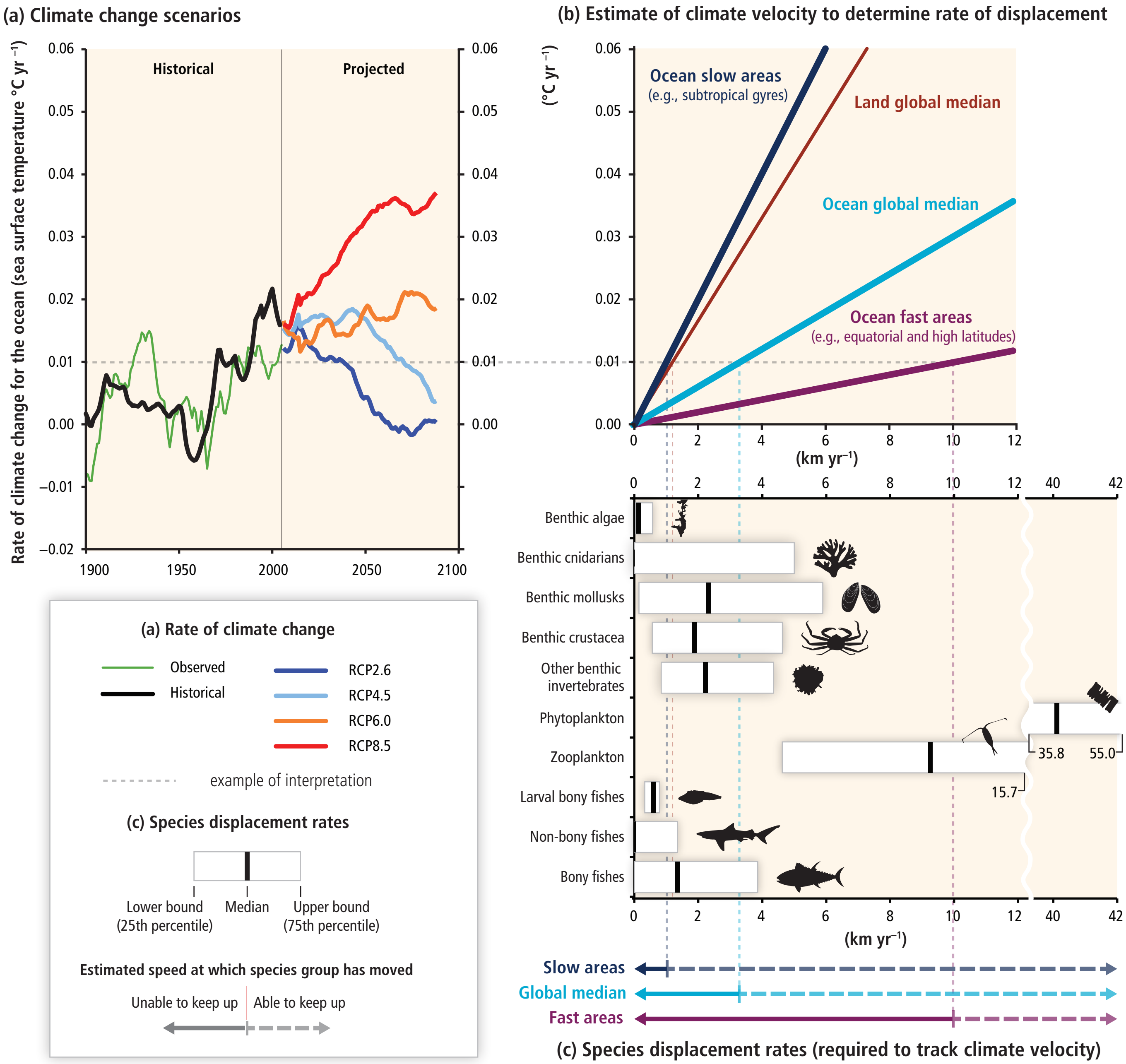

Figure MB-3 | (a) Rate of climate change for the ocean (sea surface temperature (SST) °C yr⁻¹). (b) Corresponding climate velocities for the ocean and median velocity from land (adapted from Burrows et al., 2011). (c) Observed rates of displacement of marine taxonomic groups based on observations over 1900–2010. The dotted bands give an example of interpretation. Rates of climate change of 0.01 °C yr⁻¹ correspond to approximately 3.3 km yr⁻¹ median climate velocity in the ocean. When compared to observed rates of displacement (c), many marine taxonomic groups have been able to track these velocities. For phytoplankton and zooplankton the rates of displacement greatly exceed median climate velocity for the ocean and, for phytoplankton exceed velocities in fast areas of the ocean approximately 10.0 km yr⁻¹. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (a) Observed rates of climate change for ocean SST (green line) are derived from the Hadley Centre Interpolated SST 1.1 (HadISST1.1) data set, and all other rates are calculated based on the average of the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles (Table SM30-3) for the historical period and for the future based on the four Representative Concentration Pathway (RCP) scenarios. Data were smoothed using a 20-year sliding window. (b) Median climate velocity over the global ocean surface (light blue line; excluding polar seas) calculated from HadSST1.1 data set over 1960–2009 using the methods of Burrows et al. (2011). Median velocities representative of ocean regions of slow velocities such as the Pacific subtropical gyre (dark blue line) and of high velocities such as the Coral Triangle or the North Sea (purple line) shown. Median rates over global land surface (red line) over 1960–2009 calculated using Climate Research Unit data set CRU TS3.1. Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2009. (c) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. (2013) using published studies. Note the displacement rates for phytoplankton exceed the axis, so values are given.

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OA

Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, Section 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulfur all exacerbate ocean acidification locally (Sections 5.3.3.6, 6.1.1, 30.3.2.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Figure CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30-8, 30-9). Projected changes in open ocean, surface water chemistry for the year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to pre-industrial values range from a pH change of –0.14 units with Representative Concentration Pathway (RCP)2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 units with RCP8.5 (936 ppm CO_2, +3.7°C, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (Sections 5.3.3.5, 30.3.2.2), in polar regions (WGI Section 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several meta-analyses (Sections 6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; Sections 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Figure OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories, and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; Sections 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; Sections 5.4.2.3, 6.3.2.2, 6.3.2.3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves, and gastropods, reducing the competitiveness with non-calcifiers (Sections 5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4). Some corals and temperate fishes experience disturbances to behavior, navigation, and their ability to tell conspecifics from predators (Section 6.3.2.4). However, there is no evidence for these effects to persist on evolutionary time scales in the few groups analyzed (Section 6.3.2).

Some phytoplankton and molluscs displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; Section 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; Section 6.1.2).

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator–prey relationships and competitive interactions (Sections

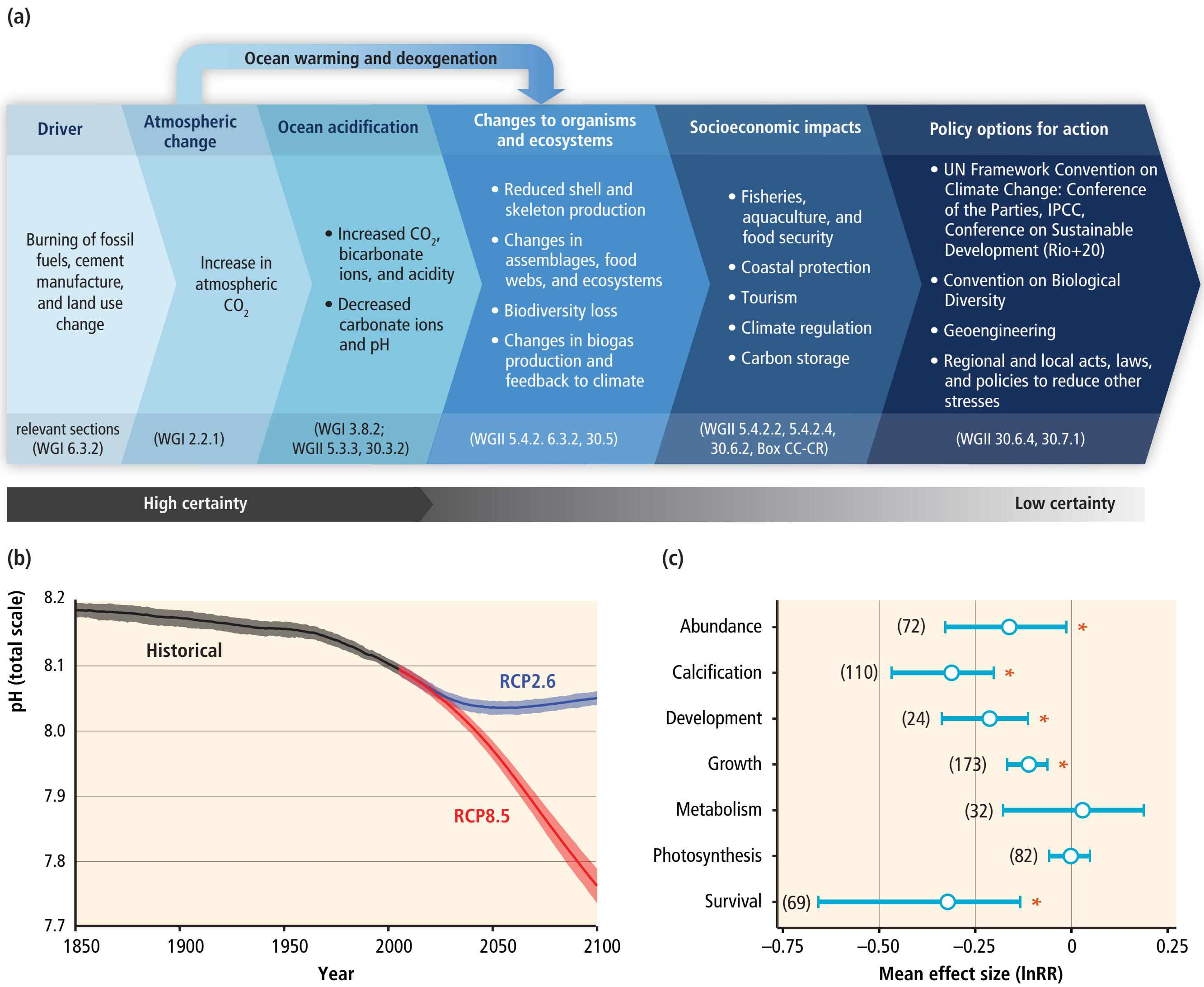

Figure OA-1 | (a) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). (b) Multi-model simulated time series of global mean ocean surface pH (on the total scale) from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations from 1850 to 2100. Projections are shown for emission scenarios Representative Concentration Pathway (RCP)2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (gray shading) is the modeled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations (WGI AR5 Figures SPM.7 and TS.20). (c) Effect of near-future acidification (seawater pH reduction of ≤0.5 units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The * denotes a statistically significant effect.

6.3.2.5, 6.3.5, 6.3.6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity of communities (Box CC-CR; Sections 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (Section 5.4.2.2).

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts, and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (Section 6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, Section 5.4.2.4) and the goods and services that they provide such as fisheries, tourism, and coastal protection (*limited evidence, high agreement*; Box CC-CR; Sections 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed because of the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (Section 19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially exploited shelled molluscs (Section 6.4.1.1) would result in a reduction of USA production of 3 to 13% according to the Special Report on Emission Scenarios (SRES) A1FI emission scenario (*low confidence*). The global cost of production loss of molluscs could be more than US$100 billion by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Section 6.4.1.1). The annual economic damage of ocean-acidification–induced coral reef loss by 2100 has been estimated, in 2012, to be US$870 and 528 billion, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; Section 6.4.1). Although this number is small compared to global gross domestic product (GDP), it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (Sections 25.7.5, 29.3.1.2).

OA

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO_2) and/or adaptation by reducing the consequences of past and future ocean acidification (Section 6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (Section 6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (Section 6.4.2.2). Geoengineering techniques to remove CO_2 from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (Section 6.4.2.2). In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Sections 6.4.2.2, 30.3.2.3, 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (Section 6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (Section 5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (Section 6.4.2.1).

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PP

Net Primary Production in the Ocean

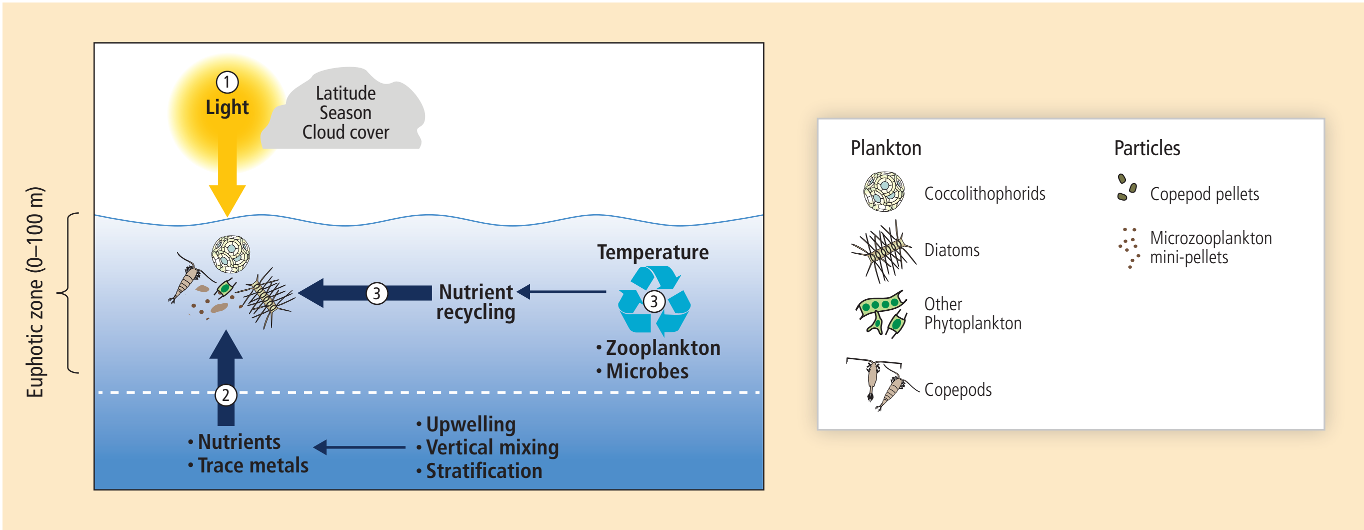
Philip W. Boyd (New Zealand), Svein Sundby (Norway), Hans-Otto Pörtner (Germany)

Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (Sections 6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, CO_2, and temperature (Figure PP-1a). These drivers, in turn, are influenced by oceanic and atmospheric processes, including cloud cover; sea ice extent; mixing by winds, waves, and currents; convection; density stratification; and various forms of upwelling induced by eddies, frontal activity, and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea ice extent (Figure PP-1a). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI AR5, Chapter 3), and on ecosystem structure and functioning (*medium confidence*; Sections 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity with nutrient-poor subtropical waters and light-limited Arctic waters at the lower range and productive upwelling regions and highly eutrophic coastal regions at the upper range (Figure PP-1b).

The oceans currently provide ~50×10^{15} g C yr^{-1}, or about half of global NPP (Field et al., 1998). Global estimates of NPP are obtained mainly from satellite remote sensing (Section 6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the Northeast Pacific (Hamme et al., 2010). Climate variability can drive pronounced changes in NPP (Chavez et al., 2011), such as from El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez et al., 1999).

Multi-year time series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld et al. (2006), using satellite data, reported a prolonged and sustained global NPP decrease of 190×10^{12} g C yr^{-1}, for the period 1999–2005—an annual reduction of 0.57% of global NPP. In contrast, a time series of directly measured NPP between 1988 and 2007 by Saba et al. (2010) (i.e., *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2% yr^{-1}) in NPP for two low-latitude open ocean sites. This discrepancy between *in situ* and remotely sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba et al., 2010, 2011). Modeling studies have subsequently revealed that the <15-year archive of satellite-

(a)



(b)

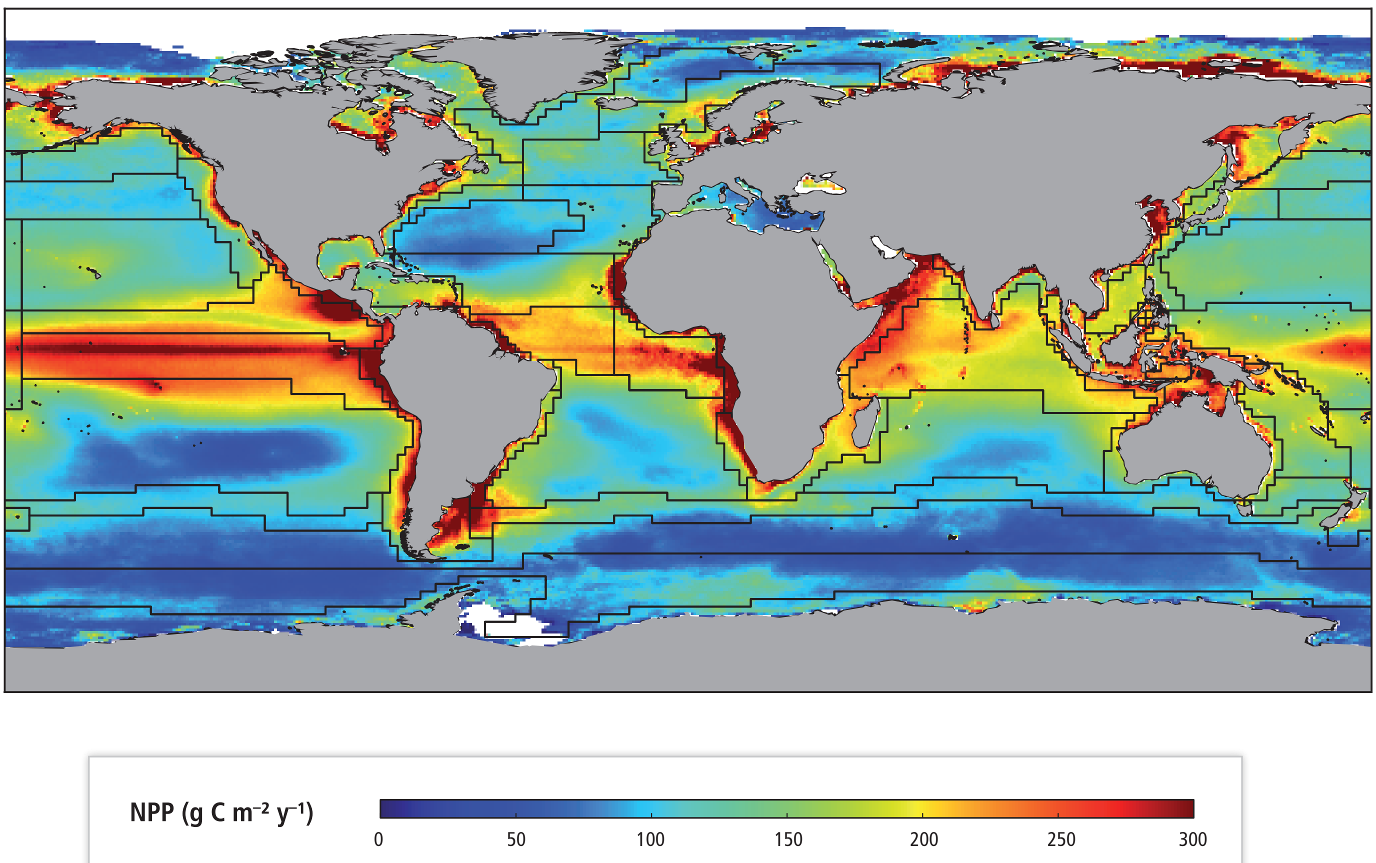


Figure PP-1 | (a) Environmental factors controlling Net Primary Production (NPP). NPP is controlled mainly by three basic processes: (1) light conditions in the surface ocean, that is, the photic zone where photosynthesis occurs; (2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, and (3) regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical, and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. (b) Annual composite map of global areal NPP rates (derived from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite climatology from 2003–2012; NPP was calculated with the Carbon-based Productivity Model (CbPM; Westberry et al., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. White areas = no data. (Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.)

derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson et al., 2010; Beaulieu et al., 2013). Although multi-decadal, the available time series of oceanic NPP measurements are also not of sufficient duration relative to the time scales of longer-term climate variability modes as for example Atlantic Multi-decadal Oscillation (AMO), with periodicity of 60-70 years, Figure 6-1). Recent attempts to synthesize longer (i.e., centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce et al., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate–ocean biogeochemical Earth System Models (WGI AR5 Chapter 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP, particularly in the high-latitude biomes (Steinacher et al., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macronutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the euphotic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 2000 under a high emission scenario (Polovina et al., 2011; SRES (Special Report on Emission Scenarios) A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp et al., 2013), which project decreases in global NPP by 8.6 (±7.9), 3.9 (±5.7), 3.6 (±5.7), and 2.0 (±4.1) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5, and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g., from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional scales (i.e., provinces, see Figure PP-1b).

Model projections had predicted a range of changes in global NPP from an increase (relative to preindustrial rates) of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0; Sarmiento et al., 2004; Schmittner et al., 2008) to a decrease of 2-20% under the SRES A2 emission scenario (Steinacher et al., 2010). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g., Moore et al., 2009; Boyd et al., 2010). This may lead to an underestimation of NPP (Mohr et al., 2010; Mulholland et al., 2012; Wilson et al., 2012), however, the extent of such underestimation is unknown (Luo et al., 2012).

Care must be taken when comparing global, provincial (e.g., low-latitude waters, e.g., Behrenfeld et al., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea ice–free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of $8.1x10^{12}$ g C yr^{-1} between 1998 and 2009. Other regional trends in NPP are reported in Sections 30.5.1 to 30.5.6. In addition, although future model projections of global NPP from different models (Steinacher et al., 2010; Bopp et al., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low- (SRES B1 or RCP4.5) and high-emission scenarios (*medium confidence*; SRES A2 or RCPs 6.0, 8.5, Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

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PP

RC

Regional Climate Summary Figures

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Information about the likelihood of regional climate change, assessed by Working Group I (WGI), is foundational for the Working Group II assessment of climate-related risks. To help communicate this assessment, the regional chapters of WGII present a coordinated set of regional climate figures, which summarize observed and projected change in annual average temperature and precipitation during the near term and the longer term for RCP2.6 and RCP8.5. These WGII regional climate summary figures use the same temperature and precipitation fields that are assessed in WGI Chapter 2 and WGI Chapter 12, with spatial boundaries, uncertainty metrics, and data classes tuned to support the WGII assessment of climate-related risks and options for risk management. Additional details on regional climate and regional climate processes can be found in WGI Chapter 14 and WGI Annex 1.

The WGII maps of observed annual temperature and precipitation use the same source data, calculations of data sufficiency, and calculations of trend significance as WGI Chapter 2 and WGI Figures SPM.1 and SPM.2. (A full description of the observational data selection and significance testing can be found in WGI Box 2.2.) Observed trends are determined by linear regression over the 1901–2012 period of Merged Land–Ocean Surface Temperature (MLOST) for annual temperature, and over the 1951–2010 period of Global Precipitation Climatology Centre (GPCC) for annual precipitation. Data points on the maps are classified into three categories, reflecting the categories used in WGI Figures SPM.1 and SPM.2:

1) Solid colors indicate areas where (a) sufficient data exist to permit a robust estimate of the trend (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), and (b) the trend is significant at the 10% level (after accounting for autocorrelation effects on significance testing).
2) Diagonal lines indicate areas where sufficient data exist to permit a robust estimate of the trend, but the trend is not significant at the 10% level.
3) White indicates areas where there are not sufficient data to permit a robust estimate of the trend.

The WGII maps of projected annual temperature and precipitation are based on the climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapters 12, 14, and Annex I). The CMIP5 archive includes output from Atmosphere–Ocean General Circulation Models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, vary between the different CMIP5 experiments. The WGII regional climate maps use the same source data as WGI Chapter 12 (e.g., Box 12.1 Figure

1), including the WGI multi-model mean values; the WGI individual model values; the WGI measure of baseline ("internal") variability; and the WGI time periods for the reference (1986–2005), mid-21st century (2046–2065), and late-21st century (2081–2100) periods. The full description of the selection of models, the selection of realizations, the definition of internal variability, and the interpolation to a common grid can be found in WGI Chapter 12 and Annex I.

In contrast to the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007), which used the IPCC Special Report on Emission Scenarios (SRES) emission scenarios (IPCC, 2000), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to characterize possible trajectories of climate forcing over the 21st century. The WGII regional climate projection maps include RCP2.6 and RCP8.5, which represent the high and low end of the RCP range at the end of the 21st century. Projected changes in global mean temperature are similar across the RCPs over the next few decades (Figure RC-1; WGI Figure 12.5). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. In addition, societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, the magnitude of global temperature increase diverges across the RCPs (Figure RC-1; WGI Figure 12.5). For this longer-term era of climate options, near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change. The benefits of mitigation and adaptation thereby occur over different but overlapping time frames, and present-day choices thus affect the risks of climate change throughout the 21st century.

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figures RC-2 and RC-3), categorized into four classes. The classes are constructed based on the IPCC uncertainty guidance, providing a quantitative basis for assigning likelihood (Mastrandrea et al., 2010), with *likely* defined as 66 to 100% and *very likely* defined as 90 to 100%.

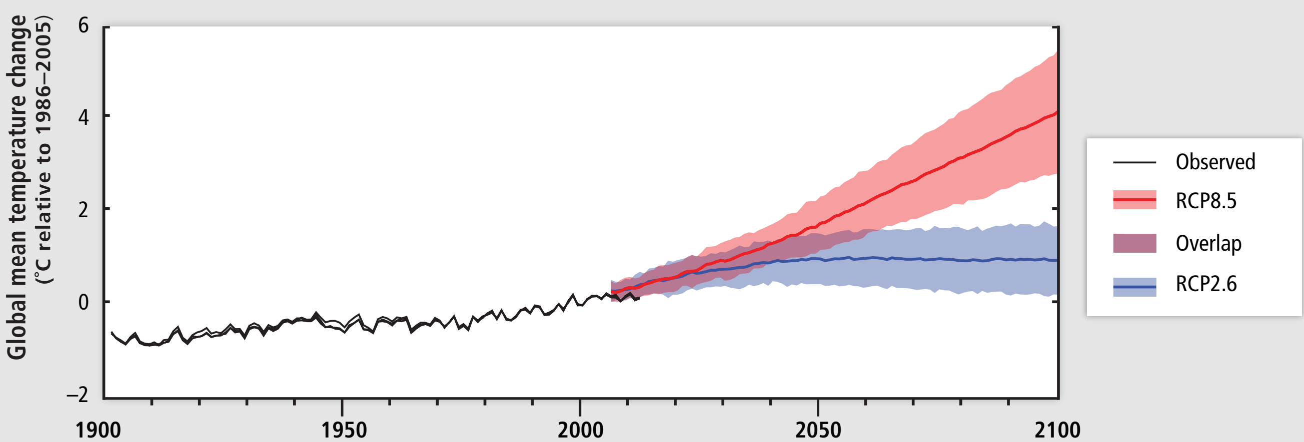

Figure RC-1 | Observed and projected changes in global annual average temperature. Values are expressed relative to 1986–2005. Black lines show the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP), National Climate Data Center Merged Land–Ocean Surface Temperature (NCDC-MLOST), and Hadley Centre/Climatic Research Unit gridded surface temperature data set 4.2 (HadCRUT4.2) estimates from observational measurements. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for Representative Concentration Pathway (RCP) 2.6 and 39 models for RCP8.5.

The classifications in the WGII regional climate projection figures are based on two aspects of likelihood (e.g., WGI Box 12.1 and Knutti et al., 2010). The first is the likelihood that projected changes exceed differences arising from internal climate variability (e.g., Tebaldi et al., 2011). The second is agreement among models on the sign of change (e.g., Christensen et al., 2007; and IPCC, 2012).

The four classifications of projected change depicted in the WGII regional climate maps are:

1) Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means), and greater than or equal to 90% of models agree on sign of change. These criteria (and the areas that fall into this category) are identical to the highest confidence category in WGI Box 12.1. This category supersedes other categories in the WGII regional climate maps.
2) Colors with white dots indicate areas with strong agreement, where 66% or more of models show change greater than the baseline variability, and 66% or more of models agree on sign of change.
3) Gray indicates areas with divergent changes, where 66% or more of models show change greater than the baseline variability, but fewer than 66% agree on sign of change.
4) Colors with diagonal lines indicate areas with little or no change, where fewer than 66% of models show change greater than the baseline variability. It should be noted that areas that fall in this category for the annual average could still exhibit significant change at seasonal, monthly, and/or daily time scales.

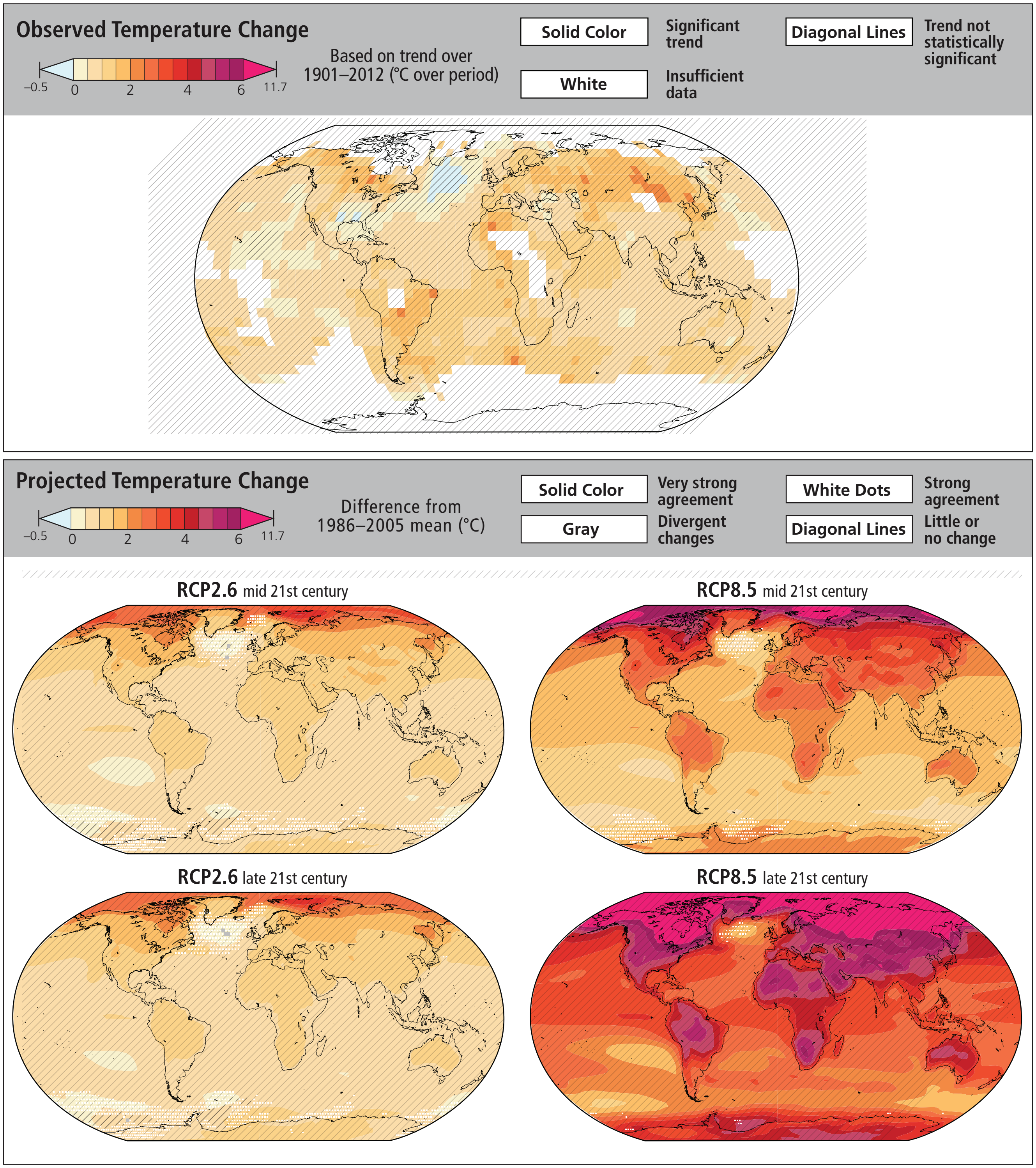

Figure RC-2 | Observed and projected changes in annual average surface temperature. (A) Map of observed annual average temperature change from 1901 to 2012, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –0.53 to +2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections of annual average temperature changes for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: +0.19 to +4.08°C for mid 21st century of RCP2.6; +0.06 to +3.85°C for late 21st century of RCP2.6; +0.70 to +7.04°C for mid 21st century of RCP8.5; and +1.38 to +11.71°C for late 21st century of RCP8.5.

RC

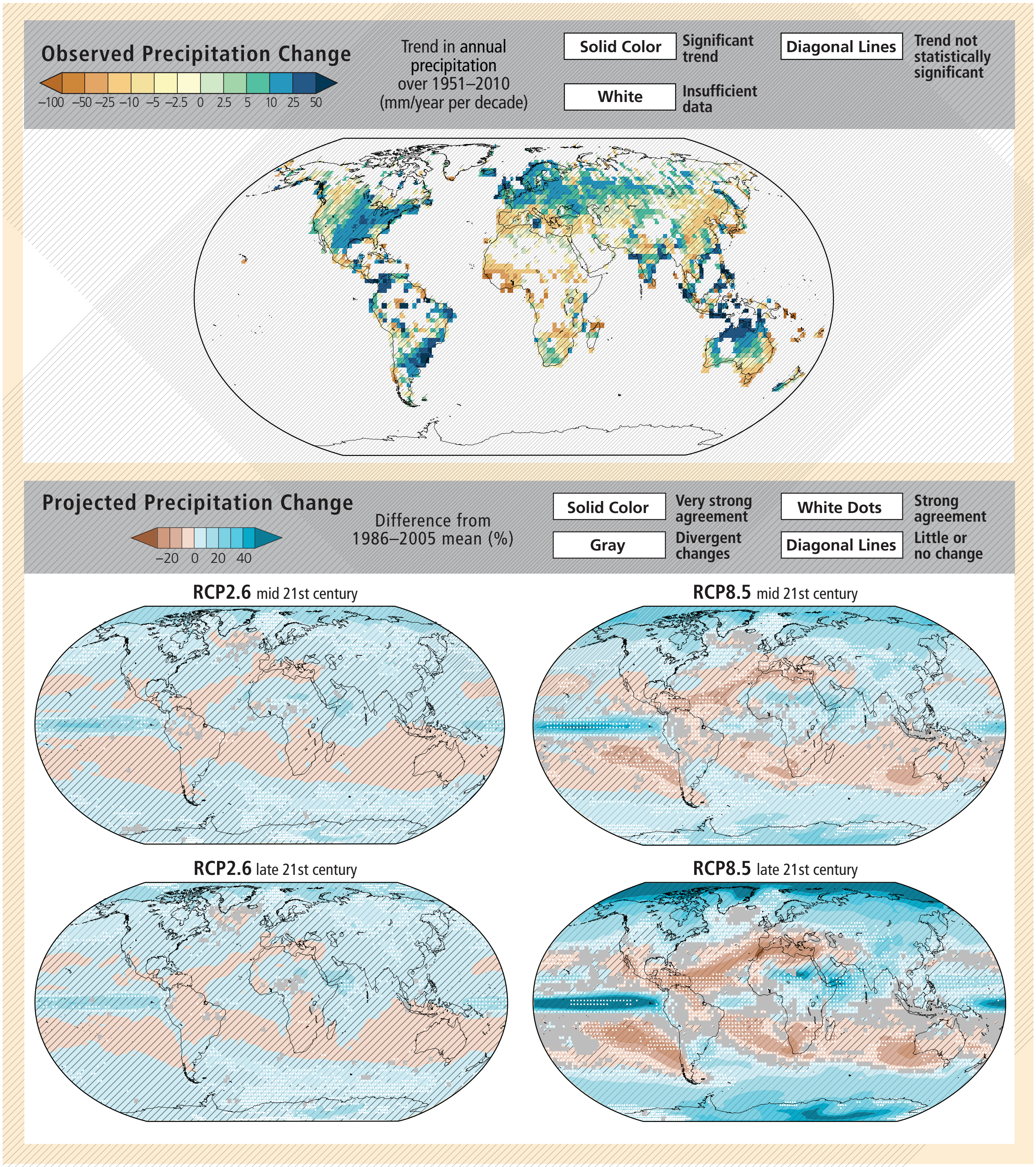

Figure RC-3 | Observed and projected changes in annual average precipitation. (A) Map of observed annual precipitation change from 1951–2010, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –185 to +111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: –10 to +24% for mid 21st century of RCP2.6; –9 to +22% for late 21st century of RCP2.6; –19 to +57% for mid 21st century of RCP8.5; and –34 to +112% for late 21st century of RCP8.5.

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RF

Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

Petra Döll (Germany), Stuart E. Bunn (Australia)

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff et al., 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e., changes to the frequency, magnitude, duration, and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino et al., 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*; Xenopoulos et al., 2005; Aldous et al., 2011). By the 2050s, climate change is projected to impact river flow characteristics such as long-term average discharge, seasonality, and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (Special Report on Emission Scenarios (SRES) A2 emissions, Met Office Hadley Centre climate prediction model 3 (HadCM3)), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, that is, with a lower spring flood and increased runoff during winter months (Renofalt et al., 2010).

Because biota are often adapted to a certain level of river flow variability, the projected larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke et al., 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah et al., 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5 to 7% of the global land area, mainly in semiarid areas (Döll and Müller Schmied, 2012; see Table 3-2 in Chapter 3).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme et al., 2010). Eco-regions containing more than 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme et al., 2010).

As a result of increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows, and possibly reduced summer low flows (Section 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20 to 40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin et al., 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart et al., 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer et al., 2009).

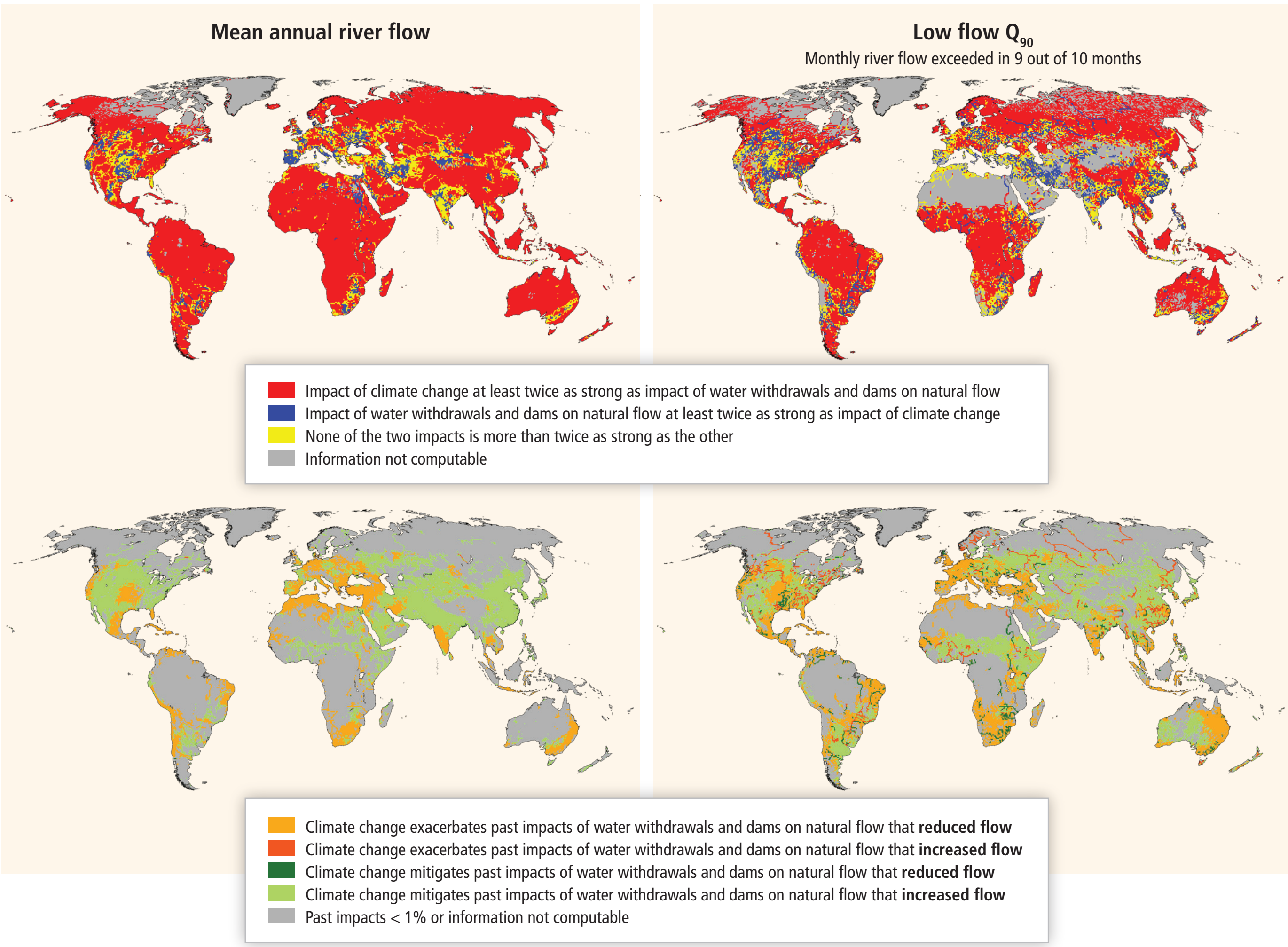

Figure RF-1 | Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961–1990 and 2041–2070 according to the emissions scenario A2 as implemented by the global climate model Met Office Hadley Centre Coupled Model, version 3 (HadCM3). Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett et al., 2005; Vuille et al., 2008; Jacobsen et al., 2012). In the first phase, when river discharge is increased as a result of intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream flow may have negative impacts on narrow range endemics (Jacobsen et al., 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C, and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C, and 3.8°C, respectively (van Vliet et al., 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet et al., 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

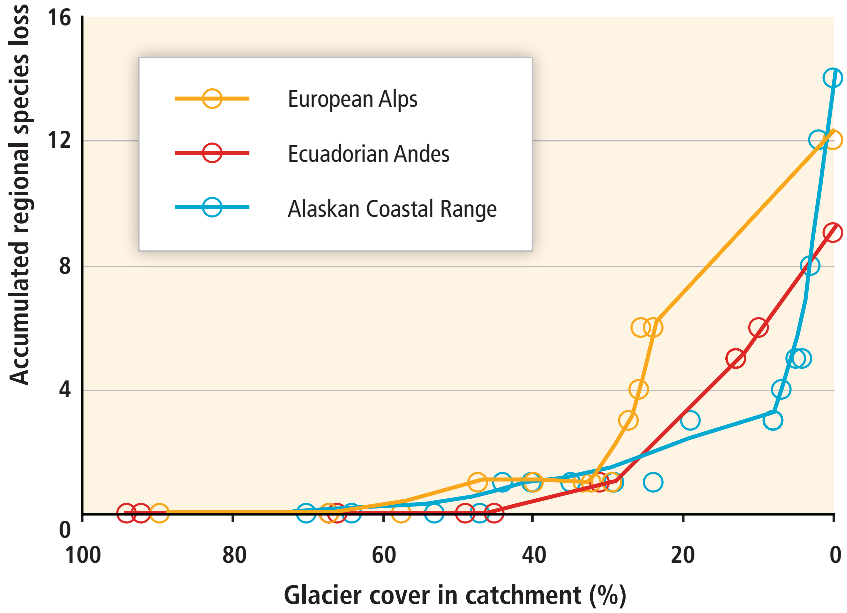

Figure RF-2 | Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9 to 14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16, and 38% of the total species richness in the three study regions in Ecuador, Europe, and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site (Europe or Ecuador) or date (Alaska), and lines are Lowess fits. (Adapted by permission from Jacobsen et al., 2012.)

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TC

Building Long-Term Resilience from Tropical Cyclone Disasters

Yoshiki Saito (Japan), Kathleen McInnes (Australia)

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves, and storm surge, all of which can have major impacts on society and ecosystems. Bangladesh and India suffer 86% of mortality from tropical cyclones (Murray et al., 2012), which occurs mainly during the rarest and most severe storm categories (i.e., Categories 3, 4, and 5 on the Saffir–Simpson scale).

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques, particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities, which leads to *low confidence* that any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e., maximum wind speed and rainfall rates) is *likely* to increase (WGI AR5 Section 14.6). Regionally specific projections have *lower confidence* (see WGI AR5 Box 14.2).

Longer-term impacts from tropical cyclones include salinization of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer-term changes associated with climate change.

Asian deltas are particularly vulnerable to tropical cyclones owing to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused more than 0.5 million fatalities (Murray et al., 2012), for example, cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on May 2, 2008 and caused more than 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA Moderate Resolution Imaging Spectrometer (MODIS) image on May 5, 2008 (see Figure TC-1).

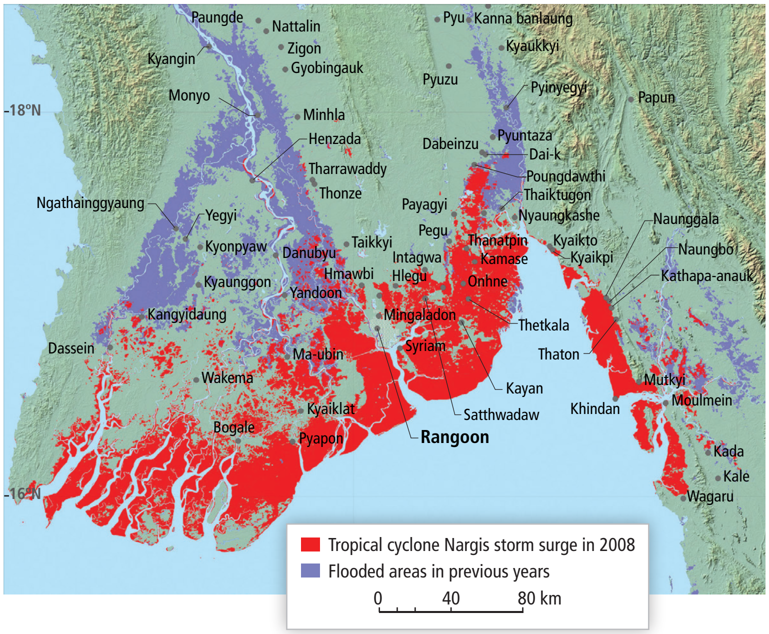

Figure TC-1 | The intersection of inland and storm surge flooding. Red shows May 5, 2008 Moderate Resolution Imaging Spectrometer (MODIS) mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The purple areas to the north were flooded by the river in prior years. (Source: Brakenridge et al., 2013.)

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation. Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3400 compared to more than 138,000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Disaster risk management strategies for tropical cyclones in coastal areas create protective measures, anticipate and plan for extreme events, and increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). However, Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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UP

Uncertain Trends in Major Upwelling Ecosystems

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Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These conditions trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the planet, the Equatorial Upwelling System (EUS; Section 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE; Section 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25% to global fish production (Figure 30.1B, Table SM30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of "bottom-up" trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds, and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI Sections 3.2, 3.3, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, owing to the uncertainty in wind speed trends (WGI Section 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the late 1990s (WGI Section 3.4.4). Observations and modeling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the difference in rates of heat gain between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping and the upwelling of nutrient-rich, cold waters (Figure CC-UP). Some regional records support this hypothesis; others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems, making it difficult to predict changes in the intensity of all Eastern EBUEs (Section 30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic, or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts are highly relevant because these systems provide a significant portion of global primary productivity and fishery catch (Figure 30.1 A, B; Table SM30.1). Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling, benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (*high confidence*; Sections 6.3.2, 6.3.3, 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller et al., 2010), reduce fisheries' catch potential, and impact aquaculture in coastal areas (Barton et al., 2012; see also Sections 5.4.3.3, 6.3.3, 6.4.1, 30.5.1.1.2, 30.5.5.1.3). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulfide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor. This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004; Bakun et al., 2010), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya et al., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (Section 6.4.1, Chapter 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean, upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch et al., 2007; Deutsch and Weber, 2012), but field observations of N_2 fixation in these regions have not supported these predictions (Fernandez et al., 2011; Franz et al., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending on pCO_2 of the upwelled water, and potentially increasingly impact the biota of EBUEs.

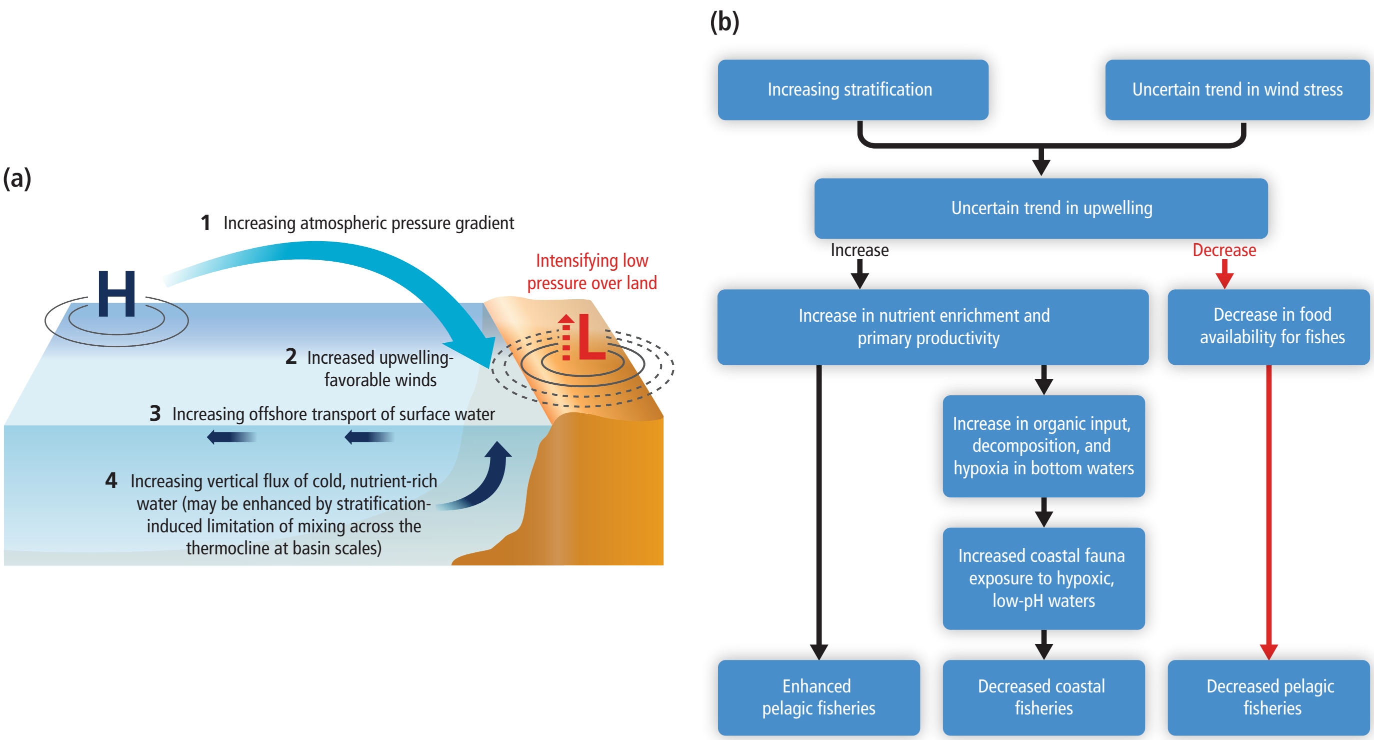

Figure UP-1 | (a) Hypothetic mechanism of increasing coastal wind–driven upwelling at Equatorial and Eastern Boundary upwelling systems (EUS, EBUE, Figure 30-1), where differential warming rates between land and ocean results in increased land–ocean (1) pressure gradients that produce (2) stronger alongshore winds and (3) offshore movement of surface water through Ekman transport, and (4) increased upwelling of deep cold nutrient rich waters to replace it. (b) Potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decrease coastal fisheries due to an increased exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

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UR

Urban–Rural Interactions – Context for Climate Change Vulnerability, Impacts, and Adaptation

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Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural–urban boundaries to become less well defined, and new types of land use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

1) Climate extremes in rural areas resulting in urban impacts— teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities.
2) Events specific to the rural–urban interface— given the highly integrated nature of rural–urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities, and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health.
3) Integrated infrastructure and service disruption—as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, and economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. Although in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River that led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban areas is rural–urban migration. There have been cases where migration and urbanization patterns have been to attributed to climate change or its proxies such as in parts of Africa (Morton, 1989; Barrios et al., 2006). However, as recognized by Black et al. (2011), life in rural areas across the world typically involves complex patterns of rural–urban and rural–rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon et al. (2006, p. 4) assert that the simple dichotomy between "rural" and "urban" has "long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South." One approach to reconciling this is through the increasing application of the concept of "peri-urban areas" (Simon et al., 2006; Simon, 2008). These areas can be seen as rural locations that have "become more urban in character" (Webster, 2002, p. 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be "largely rural landscapes" (Learner and Eakin, 2010, p. 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of "core" urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural–urban migration and by structural adjustment (e.g., withdrawal of food price controls and food subsidies). Lerner and Eakin (2011; also Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labor: buffering of risk from insecure urban labor markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural–urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarized as specifically combining urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation, and invisibility to policymakers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the coexistence of rural and urban perspectives, which may give rise to conflicts between different social/interest groups and economic activities (Masuda and Garvin, 2008; Solona-Solona 2010; Darly and Torre, 2013).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher, 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policymakers at both local and national levels, and may suffer from a lack of necessary services and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups, for example, do not reach peri-urban farmers (Liwenga et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts, suburban–exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2010). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural–urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labor markets and wage labor in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural–urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land use conversion in rural areas, for example, wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential, and recreational uses in the Philippines (Kelly, 1998) have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate-induced reductions in water availability may be more of a concern than population growth or increased per capita use for securing continued supplies of water to large cities (Jenerette and Larsen, 2006), which requires an innovative approach to address such conflicts (Pearson et al., 2010).

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VW

Active Role of Vegetation in Altering Water Flows under Climate Change

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Climate, vegetation, and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e., by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g., higher temperature or altered precipitation) on vegetation structure, biomass production, and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modeling experiments (e.g., Leakey et al., 2009; Reddy et al., 2010; de Boer et al., 2011). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, that is, lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C_3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas et al., 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and in a temperate semi-natural grassland (Koehler et al., 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen et al., 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan et al., 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modeling study by Gedney et al., 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao et al., 2007; Gerten et al., 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Andreu-Hayles et al., 2011; Peñuelas et al., 2011). However, basal area measurements at more than 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis et al., 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon et al., 2010). Satellite observations analyzed in Donohue et al. (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modeling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney et al. (2006) that suggested that the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat et al. (2004). However, a more recent analysis based on a more complete data set (Dai et al., 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland et al., 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao et al., 2007; Gerten et al., 2008; Alkama et al., 2011; Sterling et al., 2013). Oliveira et al. (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. Twenty-first century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts et al., 2007; Murray et al., 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten et al., 2011; Wiltshire et al., 2013). In absolute terms, the isolated effect of CO_2 has been modeled to increase future global runoff by 4 to 5% (Gerten et al., 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were in Nugent and Matthews, 2012). In a global model intercomparison study (Davie et al., 2013), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with the above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure, and plant growth is a source of uncertainty, as also suggested by Cao et al. (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher et al., 2009) and enhance the contrast between land and ocean surface warming (Joshi et al., 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama et al., 2010).

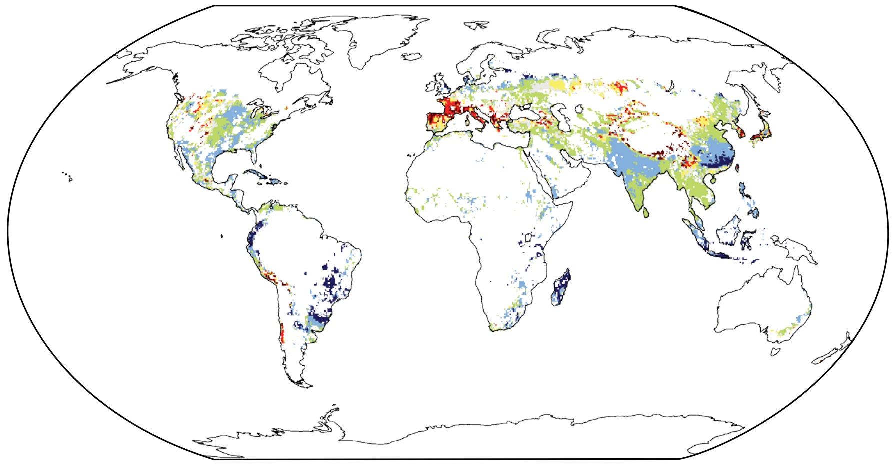
VW

An application of a soil–vegetation–atmosphere–transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum et al., 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, that is, increasing WUE and either increasing or decreasing leaf area (Crosbie et al., 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green et al., 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma et al., 2010).

Using a large ensemble of climate change projections, Konzmann et al. (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader et al., 2010). However, substantial CO_2-driven improvements will be realized only if proper management abates limitation of plant growth by nutrient availability or other factors.

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg et al., 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port et al., 2012; Saatchi et al., 2013). One model in the study by Davie et al. (2013) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon, and vegetation dynamics evolve synchronously and interactively under climate change (Heyder et al., 2011; Gerten et al., 2013), it remains a challenge to disentangle the individual effects of climate, CO_2, and land cover change on the water cycle.

(a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO_2



(b) Impact of climate change only

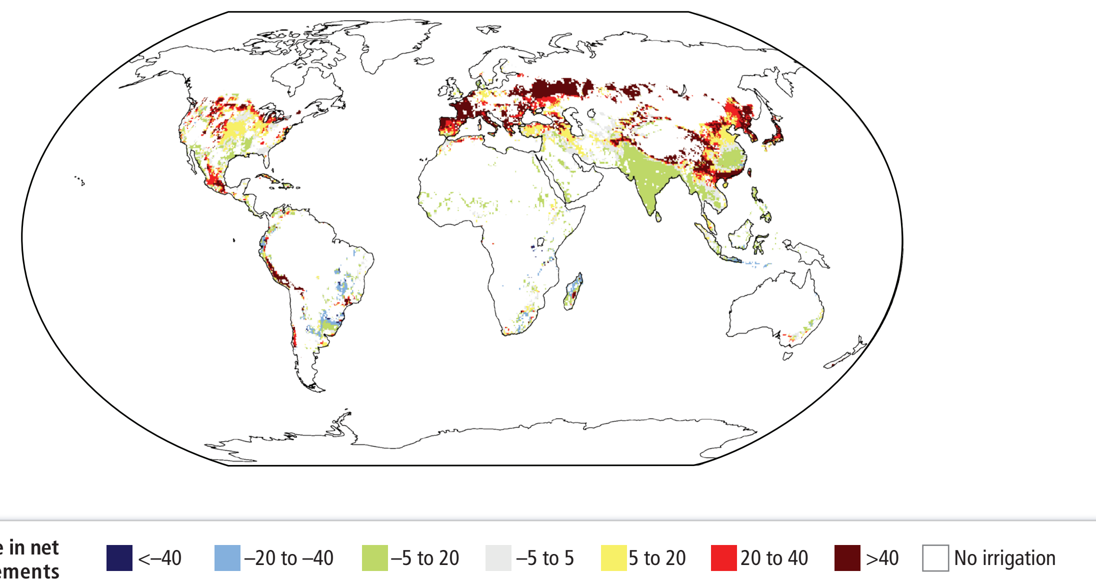


Figure VW-1 | Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. (a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (co-limitation by nutrients not considered). (b) Impact of climate change only. Shown is the median change derived from climate change projections by 19 General Circulation Models (GCMs; based on the Special Report on Emission Scenarios (SRES) A2 emissions scenario) used to force a vegetation and hydrology model. (Modified after Konzmann et al., 2013.)

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The Water–Energy–Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Energy technologies (e.g., biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2,10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber, 2008; McMahon and Price, 2011; Macknick et al., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice, and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Metcalf & Eddy, Inc. et al., 2007; Khan and Hanjra, 2009; EPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport, and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (*robust evidence, high agreement*; Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012). Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional nonrenewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Oh et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane byproducts are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale, 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence, high agreement*; Sections 10.2.2, 10.3.4, 25.7.4; and van Vliet et al., 2012; Davies et al., 2013. Water for biofuels, for example, under the International Energy Agency (IEA) Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (*medium evidence, high agreement*; WEC, 2010; Sattler et al.,

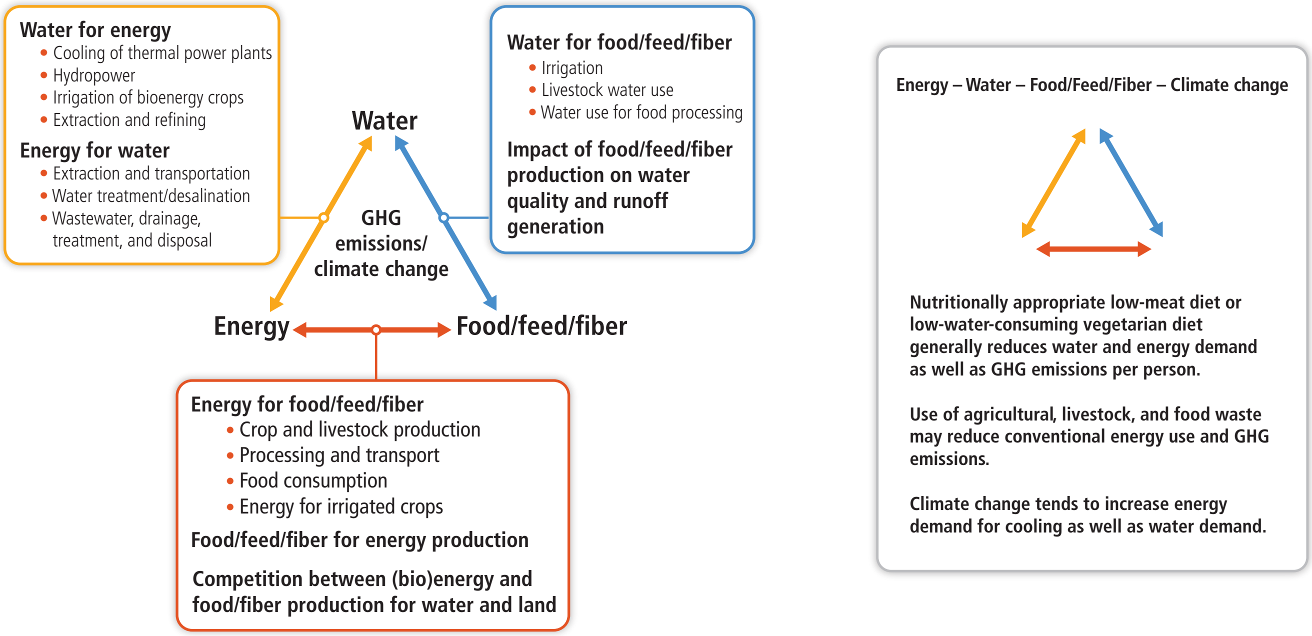

Figure WE-1 | The water–energy–food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, and energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

2012). Future water availability for energy production will change due to climate change (*robust evidence, high agreement*; Sections 3.4, 3.5.1, 3.5.2.2.

Water may require significant amounts of energy for lifting, transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater (Box 25-2, Tables 25-6, 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly—electricity use (kWh m^{-3} of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (*medium confidence*; Smit and Nasr, 1992; Jiménez-Cisneros, 1996; Qadir et al., 2007; Raschid-Sally and Jayakody, 2008). More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional freshwater and associated energy demands (Keraita et al., 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (*high confidence*; Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jiménez-Cisneros, 2009).

Linkages among water, energy, food/feed/fiber, and climate are also strongly related to land use and management (*robust evidence, high agreement*; Section 4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food, or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (*medium evidence, high agreement*; Sections 25.4.3, 25.6.2, Box 25-10). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity, and other factors (see Figure CC-WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; and air pollution reduction, as well as the implications for health and economic impacts as described throughout this Assessment Report.

The interconnectivity of food/fiber, water, land use, energy, and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel–food–land use–water–greenhouse gas (GHG) mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type, and use requirements, energy requirements, and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300 EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water, and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change is increasingly recognized as critical to effective climate resilient pathway decision making (*medium evidence, high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

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Chapters 1-20

1

Point of Departure

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Table of Contents

Executive Summary

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on human beings, their role in managing resources and natural systems, and the societal impacts of climate change. The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Characteristics in the evolution of the Working Group II assessment reports are an increasing attention to (1) adaptation limits and transformation in social and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. {1.1, 1.2}

The literature available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered by the literature has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments. Authorship of literature from developing countries has increased, although still representing a small fraction of the total. This unequal distribution of literature presents a challenge to the production of a comprehensive and balanced global assessment. {1.1.1, Figure 1-1}

Rapidly advancing climate science provides policy-relevant information that creates opportunities for decision making that can lead to climate-resilient development pathways (*robust evidence, medium agreement*). Climate change is just one of many stressors that influence resilience. The decisions that societies make within this opportunity space, also informed by observation, experience, and other factors, affect outcomes in human and natural systems. {1.1.1, 1.1.4, Figure 1-5}

Adaptation has emerged as a central area of climate change research, in country level planning, and in the implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. {1.1.4}

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement. Each finding is supported by a traceable account of the evaluation of evidence and agreement. {1.1.2.2, Box 1-1}

Impacts assessed in this report are based on climate model projections using both the IPCC Special Report on Emission Scenarios (SRES) and the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrower range in terms of emissions of ozone and aerosol precursors and related pollutants. The SRES scenarios were used in the Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). With AR5, the RCP scenarios present both emissions and greenhouse gas concentration pathways, and corresponding Shared Socioeconomic Pathways (SSPs) have been developed. The four RCPs describe different levels of mitigation leading to 21st century radiative forcing levels of about 2.6, 4.5, 6.0, and 8.5 W m^{-2}), whereas the SRES scenarios are policy-independent. {1.1.3, 1.3.3, 19.6.3.1, Boxes 21-1, 21.5.4, 24.3.3; see also WGI AR5 Chapters 1, 8, 11, 12}

1.1. The Setting

This chapter describes the information basis for the Fifth Assessment Report (AR5) of IPCC Working Group II (WGII) and the rationale for its structure. As the starting point of WGII AR5, the chapter begins with an analysis of how the literature for the assessment has developed through time and proceeds with an overview of how the framing and content of the WGII reports have changed since the first IPCC report was published in 1990. The future climate scenarios used in AR5 are a marked change from those used in the Third (TAR, 2001) and Fourth (AR4, 2007) Assessment Reports; this shift is described here, along with the new AR5 guidance for communicating scientific uncertainty. The chapter provides a summary of the most relevant key findings from the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC, 2011), the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), and the AR5 Working Group I (*The Physical Science Basis*) and AR5 Working Group III (*Mitigation of Climate Change*). Collectively these recent reports, new scenarios, and other advancements in climate change science set the stage for an assessment of impacts, adaptation, and vulnerability that could potentially overcome many of the limitations identified in the IPCC WGII AR4, particularly with respect to the human dimensions of climate change.

The critical review and synthesis of the scientific literature published since October 2006 (effective cutoff date for AR4) has required an expanded multidisciplinary approach that, in general, has focused more heavily on societal impacts and responses. This includes an assessment of impacts associated with coupled socio-ecological systems and the rapid emergence of research on adaptation and vulnerability.

WGII AR5 differs from the prior assessments primarily in the expanded outline and diversity of content that stems directly from the growth of the scientific basis for the assessment. WGII AR5 is published in two volumes (Part A: Global and Sectoral Aspects; Part B: Regional Aspects), permitting the presentation of more detailed regional analyses and an expanded coverage of the human dimensions such as adaptation. WGI AR5 was completed approximately 6 months in advance of WGII AR5, allowing the WGII authors more time to evaluate and include where possible the WGI findings; WGIII AR5 was developed almost in parallel with the WGII report.

The point of departure in the title alludes to the availability of new information concerning the interactions between climate change and other biophysical and societal stressors. Societal stressors include poverty and inequality, low levels of human development, and psychological, institutional, and cultural factors. Even in the presence of these multiple stressors, policy relevant information from scientific research, direct experience, and observation provides an opportunity space to choose and design climate-resilient development pathways (see Sections 1.1.4, 13.1.1, 14.2, 14.3; Figure 1-5).

1.1.1. Development of the Science Basis for the Assessment

The volume of literature available for assessing Climate Change Impacts, Adaptation, and Vulnerability (CCIAV) has grown significantly over the past 2 decades (Figure 1-1). A bibliometric analysis of reports produced with two bibliographic search tools (Scopus[1] and ISI Web of Science[2]) indicates that fewer than 1000 articles in journals, books, and conference proceedings were published in English on the topic of "climate change" between 1970 and 1990. By the end of 2012 the total number of such articles was reported as 102,573 (Scopus) and 62,155 (Web of Science). The current doubling rate of "climate change" publications remains short, less than 5 years: Scopus database lists 32,943 articles published between 1970 and 2005, and 76,130 published between 1970 and 2010. The number of publications per year on the topic of climate change impacts between 2005 and 2010 and on the topic of climate change adaptation between 2008 and 2010 has roughly doubled (Figure 1-1c). Thus, the total number of publications more than doubled from 2005 to 2010.

Since 1990 the geographic distribution of authors contributing to the climate change literature has expanded from Europe and North America to include a large fraction from Asia and Australasia. Literature from scientists affiliated with institutions in Africa and Central and South America, however, comprised approximately 5% of the total during 2001–2010 (Figure 1-1a). The proportion of literature focusing on individual countries within IPCC regions has also broadened over the past 3 decades, particularly for Asia (Figure 1-1b).[3] This brief chronicle neither differentiates across the various "subcategories" of the climate literature nor claims to be comprehensive in terms of literature produced in languages other than English.

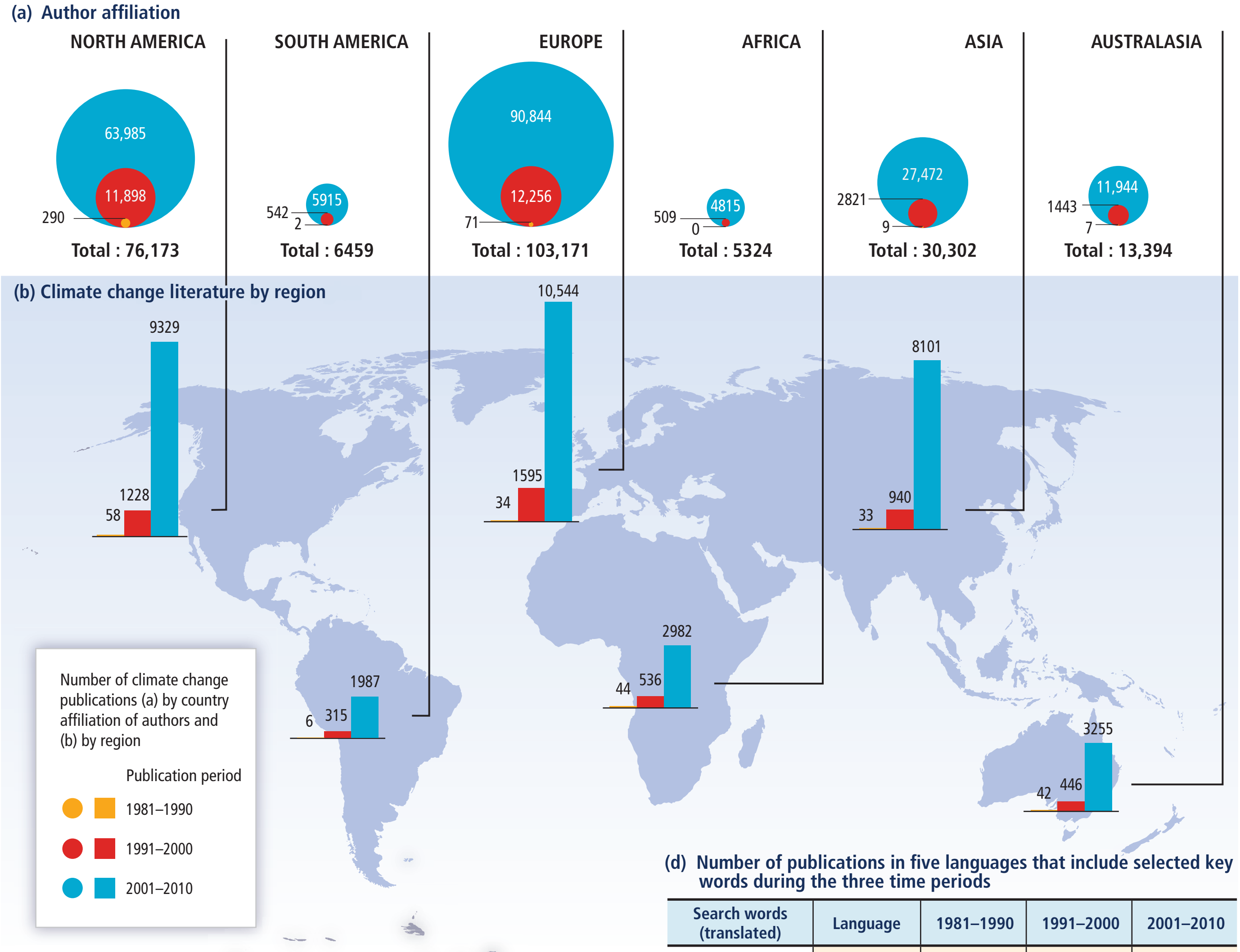
Recent growth in the total volume of literature about climate change, and in particular that devoted to impacts and adaptation, has influenced the depth and scope of assessment reports produced by WGII, and it has enabled substantial advances in the assessment of the full range of impacts, adaptation, and vulnerability (Figure 1-1c). The unequal distribution of literature (Figure 1-1a,b,d) presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. The geographical and topical distribution of literature is influenced by factors such as the availability of funding for scientific research, level of capacity building, regional experience with climate-related disasters, and the availability of long-term observational records.

Literature published on the topic of "climate change" during 1970–1990 focused primarily on changes in the physical climate system and how these changes affected other aspects of the Earth's physical environment.

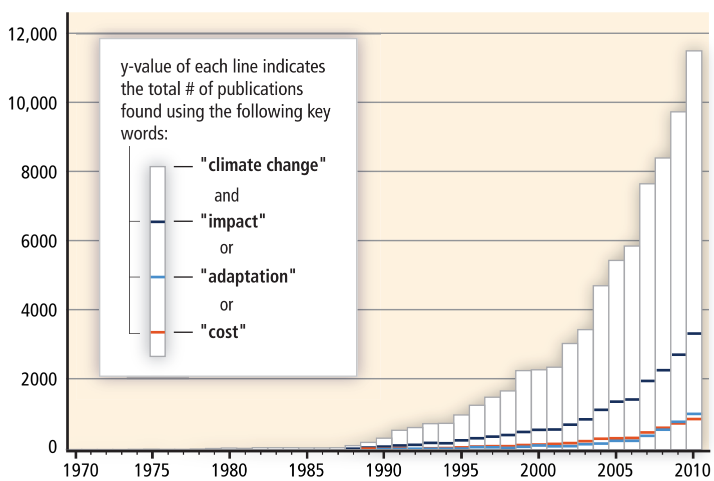
[1] Scopus is a bibliographic database owned by Elsevier that contains abstracts and citations for peer-reviewed literature in the scientific, medical, and social sciences (including arts and humanities). Scopus has more than 50 million bibliographic records (about 29 million from 1995 forward and about 21 million from 1823 to 1996), as of September 2013.

[2] Web of Science, owned by Thompson Reuters, is a bibliographic database of journals and conference proceedings for the sciences, social sciences, arts, and humanities. Web of Science includes records from over 12,000 journals and 148,000 conference proceedings dating from 1985 to present, as of September 2013.

[3] Russia, Greenland, and Iceland are included with Europe; Mexico is included with North America.



(c) Climate change literature in English, total and for selected topics (1970–2010)



(d) Number of publications in five languages that include selected key words during the three time periods

Search words (translated)	Language	1981–1990	1991–2000	2001–2010
"Climate change"	English	990	12,686	61,485
	Chinese	1454	6353	22,008
	French	1	108	815
	Russian	67	210	1443
	Spanish	3	82	1381
"Climate change" and "impacts"	English	232	3001	16,218
	Chinese	133	515	1780
	French	0	1	95
	Russian	0	72	403
	Spanish	0	7	103
"Climate change" and "adaptation"	English	14	373	3661
	Chinese	6	58	321
	French	0	7	110
	Russian	0	7	44
	Spanish	0	5	103
"Climate change" and "cost"	English	24	699	4099
	Chinese	1	22	162
	French	0	7	36
	Russian	0	1	24
	Spanish	0	2	11

Figure 1-1 | Number of climate-change publications listed in the Scopus bibliographic database and results of literature searches conducted in four other languages. (a) Number of publications in English (as of July, 2011) summed by country affiliation of all authors of climate change publications and binned into IPCC regions. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (b) Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July, 2011) binned into IPCC regions for the decades 1981–1990, 1991–2000, and 2001–2010. Each publication can be counted multiple times if more than one country is listed. (c) Annual global number of publications in English on climate change and related topics: impacts, adaptation, and costs for the years 1970–2010, as of September 2013. (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation," "impact," and "cost" (translated) in the title, abstract, or key words during the three decades ending in 2010. The following individuals conducted these literature searches during January, 2012–March, 2013: Valentin Przyluski (French), Huang Huanping (Chinese), Peter Zavialov and Vasily Kokorev (Russian), and Saúl Armendáriz Sánchez (Spanish).

Frequently Asked Questions

FAQ 1.1 | On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007?

Thousands of scientists from around the world contribute voluntarily to the work of the IPCC, which was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific assessment of the current scientific literature about climate change and its potential human and environmental impacts. Those scientists critically assess the latest scientific, technical, and socioeconomic information about climate change from many sources. Priority is given to peer-reviewed scientific, technical, and social-economic literature, but other sources such as reports from government and industry can be crucial for IPCC assessments.

The body of scientific information about climate change from a wide range of fields has grown substantially since 2007, so the new assessment reflects the large amount that has been learned in the past 6 years. To give a sense of how that body of knowledge has grown, between 2005 and 2010 the total number of publications just on climate change impacts, the focus of Working Group II, more than doubled. There has also been a tremendous growth in the proportion of that literature devoted to particular countries or regions.

The proportion of climate-change literature in engineering journals has not changed appreciably over the past 4 decades, but there was a significant increase in the proportion of literature published in biological and agricultural science journals. The proportion of the literature on the topic of "climate change" published in social science journals increased from 6% (1970s–1980s) to 9% (1990s–2000s). The themes covered by the literature on vulnerability to climate change have also expanded to issues of ethics, equity, and sustainable development. From the Scopus database, publications on the topic of climate change "impacts" crossed the threshold of 100 per year in 1991. Publications on climate change "adaptation" and societal "cost" reached this level in 2003.

Although authors continue to publish primarily in English, climate-change literature in other languages has also expanded. Literature searches in Chinese, French, Russian, and Spanish revealed a roughly fourfold or greater increase in literature published on the topic of "climate change" in each language during the past 2 decades (Figure 1-1d). Scientists from many countries tend to publish their work in English, as indicated by comparing the regional analysis and country affiliation of authors in Figure 1-1b with the results of the literature searches in the five languages. This process of "scientific internationalism," by which English becomes the primary language of scientific communication, has been described as a growing trend among Russian (Kirchik et al., 2012), Spanish (Alcaide et al., 2012), and French (Gingras and Mosbah-Natanson, 2010) researchers.

1.1.2. Evolution of the Working Group II Assessment Reports and Treatment of Uncertainty

1.1.2.1. Framing and Outlines of Working Group II Assessment Reports

The framing and contents of the IPCC WGII reports have evolved since the First Assessment Report (FAR; IPCC, 1990) as summarized in Figure 1-2. Four characteristics of this evolution are an increasing attention to (1) adaptation limits and transformation in societal and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. WGII now focuses on understanding the interactions between the natural climate system, ecosystems, human beings, and societies, this being on top of the long-standing emphasis on the biogeophysical impacts of climate change on sectors and regions.

The WGII FAR (296 pages) was organized into six major sectors: agriculture and forestry; terrestrial ecosystems; water resources; human settlements; oceans and coastal zones; and snow, ice, and permafrost. The report focused on the anticipated climate changes for a doubling of carbon dioxide (CO_2). The FAR Summary for Policymakers (SPM) highlighted the coupling of anthropogenic non-climate stresses with climate variability and greenhouse gas (GHG) driven climate change. Given the state of the science in 1990, the FAR has understandably low confidence on some high-vulnerability topics (e.g., global agricultural potential may either increase or decrease), but is more quantitative on large-scale climate impacts (e.g., climatic zones shift poleward by hundreds of kilometers). Health impacts were vague, emphasizing ozone depletion and ultraviolet-B (UV-B) damage. The IPCC WGII 1992 Supplementary Report followed with four assigned topics (regional climate change; energy; agriculture and forestry; sea level rise) and was primarily a strategy report, for example, urging that studies of change in tropical cyclones are of highest priority (IPCC, 1992).

For the IPCC SAR (IPCC, 1996) WGII reviewed climate change impacts, vulnerability, and adaptation plus mitigation options for GHGs. There were two introductory primers, 18 chapters on impacts and adaptation (e.g., forests, rangelands, deserts, human settlements, agriculture, fisheries, financial services, human health), and seven chapters on sectoral mitigation (e.g., energy, industry, forests) but with cost analysis left to WGIII. The SAR made use of the new IPCC 1992 scenarios (IS92). Projections of 2100 sea level rise (15 to 95 cm) and temperature increase (1.0°C to 3.5°C) were similar to the FAR's doubled-CO_2 scenario.

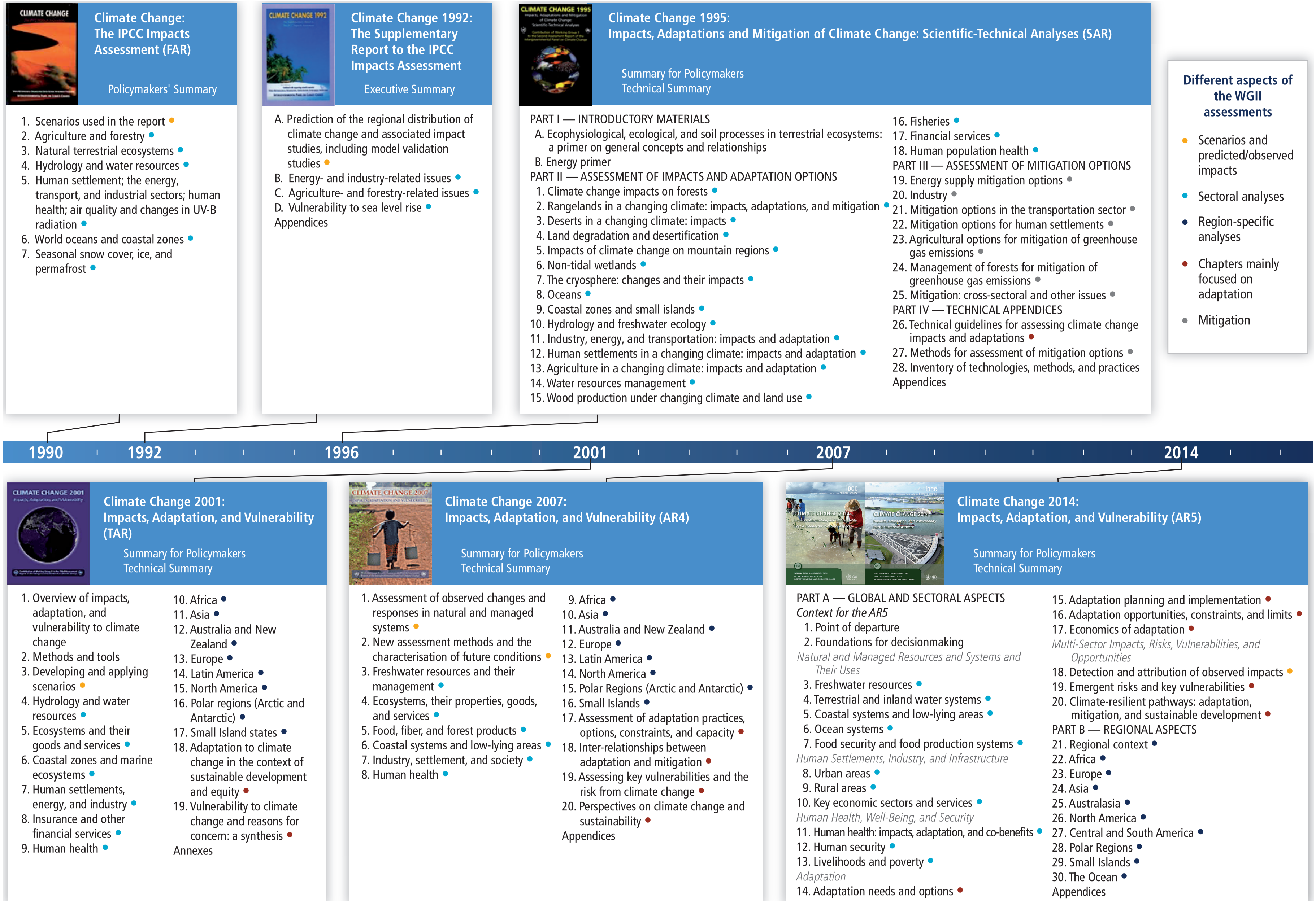


Figure 1-2 | Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The First Assessment Report (FAR; IPCC, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change. For the Second Assessment Report (SAR; IPCC, 1996) the WGII contribution included mitigation and adaptation with the impacts assessment. With the Third Assessment Report (TAR; IPCC, 2001) and Fourth Assessment Report (AR4; IPCC, 2007) climate change mitigation reverted to WGIII, and WGII remained focused on impacts, adaptation, and vulnerability with an expanded effort on the regional scale.

The SAR notes "Impacts are difficult to quantify, and existing studies are limited in scope; detection [of climate-induced changes] will be difficult," but some specifics are given (e.g., the number of people at risk of flooding from storm surges from sea level rise; the increase in malaria incidence). Vegetation models are used to map out projected changes in major biomes (see WGII SAR SPM Figure 2) – the first prediction figure in a WGII SPM.

WGII TAR (IPCC, 2001b) retained impacts, adaptation, and vulnerability, leaving the topic of mitigation to WGIII. It included five sectoral chapters (water resources, ecosystems, coastal and marine, human settlements and energy, and financial services), eight regional chapters, plus chapters on (1) adaptation, sustainable development, and equity, and (2) vulnerability and reasons for concern. The TAR made the first strong conclusion on attributing impacts: "recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems." Recent increases in floods and droughts, while affecting some human systems, could not be tied to GHG-driven climate change. The TAR introduced the "burning embers" diagram (SPM Figure 2, discussed in Chapters 18 and 19 of this report) as a way to represent "reasons for concern." The adaptive capacity, vulnerability, and key concerns for each region were laid out in detail (SPM, Table 2).

WGII AR4 (IPCC, 2007b,c) retained the basic structure of the TAR with chapters on sectors and regions. The first chapter of AR4, drawing from the expanded literature, provided an "Assessment of Observed Changes in Natural and Human Systems." AR4 incorporated several cross-chapter themes with case studies (such as impacts on deltas) as a unifying construct. Two graphics in the AR4 SPM (SPM Figure 1-2 and Table 1-1) give many examples of projected impacts of climate change, but the state of the science—both of WGI climate projections and WGII impacts—remained too uncertain at the time to give more quantitative estimates of the impacts or necessary adaptation.

This WGII fifth assessment continues and expands the sectoral and regional parts. The AR5 considers a wide and complex range of multiple stresses that influence the sustainability of human and ecological systems. The focus on climate change and related stressors, and the resulting vulnerability and risk, continues throughout this report, including the expanded "reasons for concern" (Chapters 2 and 19; see also Section 1.2.3).

1.1.2.2. Treatment of Uncertainties in IPCC Assessment Reports: A Brief History and Terms Used in the Fifth Assessment Report

An integral feature of IPCC reports is communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Treatment of uncertainties and corresponding use of calibrated uncertainty language in IPCC reports have evolved across IPCC assessment cycles (Swart et al., 2009; Mastrandrea and Mach, 2011). In WGII, the use of calibrated language began in the SAR (1996), in which most chapters used qualitative levels of confidence in Executive Summary findings. With the TAR (2001), formal guidance across the Working Groups was developed (Moss and Schneider, 2000) recognizing that "guidelines such as these will never truly be completed," and an iterative process of learning and improvement of guidance has ensued, informed by experience in each assessment cycle (IPCC, 2005; Mastrandrea et al., 2010). Each subsequent guidance paper has presented related but distinct approaches for evaluating and communicating the degree of certainty in findings of the assessment process.

The AR5 Guidance Note (summarized in Box 1-1) continues to emphasize an overriding theme of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding.

1.1.3. Scenarios Used as Inputs to Working Group II Assessments

A scenario is a storyline or image that describes a potential future, developed to inform decision making under uncertainty (Parson et al., 2007). Scenarios have been part of IPCC future climate projections since

Frequently Asked Questions

FAQ 1.2 | How is the state of scientific understanding and uncertainty communicated in this assessment?

While the body of scientific knowledge about climate change and its impacts has grown tremendously, future conditions cannot be predicted with absolute certainty. Future climate change impacts will depend on past and future socioeconomic development, which influences emissions of heat-trapping gases, the exposure and vulnerability of society and ecosystems, and societal capacity to respond.

Ultimately, anticipating, preparing for, and responding to climate change is a process of risk management informed by scientific understanding and the values of stakeholders and society. The Working Group II assessment provides information to decision makers about the full range of possible consequences and associated probabilities, as well as the implications of potential responses. To clearly communicate well-established knowledge, uncertainties, and areas of disagreement, the scientists developing this assessment report use specific terms, methods, and guidance to characterize their degree of certainty in assessment conclusions.

Box 1-1 | Communication of Uncertainty in the Working Group II Fifth Assessment

Based on the 'Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties' (Mastrandrea et al., 2010), the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations, model results, or expert judgment).

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The type and amount of evidence available vary for different topics, and that evidence can vary in quality. The consistency of different lines of evidence can also vary. Beyond consistency of evidence, the degree of agreement indicates the consensus within the scientific community on a topic and the degree to which established, competing, or speculative scientific explanations exist.

The Guidance Note provides summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams in addition evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Figure 1-3 illustrates the relationship between the summary terms for evidence and agreement and the confidence metric. There is flexibility in this relationship; increasing confidence is associated with increasing evidence and agreement, but different levels of confidence can be assigned for a given evidence and agreement statement. The degree of certainty in findings based on qualitative evidence is expressed using levels of confidence and summary terms.

In some cases, available evidence incorporates quantitative analyses, based on which uncertainties can be expressed probabilistically. In such cases, a finding can include calibrated likelihood language or a more precise presentation of probability. The likelihood terms and their corresponding probability ranges are presented below. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. When authors evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, the terms and associated meanings are:

Term*	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms used more occasionally are *extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability.

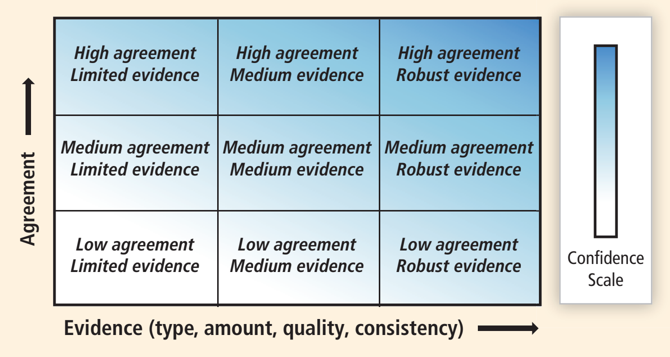


Figure 1-3 | Evidence and agreement statements and their relationship to confidence. The coloring increasing toward the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

the FAR (IPCC, 1990), where WGIII generated four scenarios (Bau = business-as-usual, B, C, and D) used by WGI to project climate change. The IPCC Supplementary Report (IPCC, 1992), a joint effort of WGI and WGIII, defined six new scenarios (IS92a–f) used in the SAR (1996). For the TAR (2001), the IPCC *Special Report on Emissions Scenarios* (SRES; Nakicenkovic et al., 2000) created many scenarios from four Integrated Assessment Models (IAMs), out of which a representative range of marker scenarios were selected (A1B, A1T, A1FI, A2, B1, B2). In the SRES, scenarios had had socioeconomic storylines but climate-mitigation options were not included. The SRES scenarios carried over into the AR4 (2007a,b) and formed the basis for the large number of ensemble climate simulations (Coupled Model Intercomparison Project Phase 3 (CMIP3)), which are still in use for climate-change studies relevant to WGII AR5.[4]

With AR5, the development of scenarios fundamentally changed from the IPCC-led SRES process. An ad hoc group of experts, anticipating AR5, built a new structure for scenarios called Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) using updated IAMs and intended to provide a flexible, interactive, and iterative approach to climate change scenarios. The four RCPs are keyed to a range of trajectories of GHG concentrations and climate forcing. They are labeled by their approximate radiative forcing (RF, W m^{-2}) that is reached during or near the end of the 21st century (RCP2.6, RCP4.5, RCP6.0, RCP8.5). The quantitative link between the socioeconomic pathway, human activities, and GHG emissions, and subsequently RF, is weaker or nonexistent with current RCP than with SRES scenarios. For example, the RCPs rely on a single parametric model (Meinshausen et al., 2011) to map from emissions to RF, whereas IPCC WGI traditionally assesses this critical linkage using the current state of scientific knowledge (see AR5 WGI Chapters 6, 11, 12, Annex II). In addition, socioeconomic scenarios, emissions, and subsequent radiative forcing pathways were not linked one-to-one in the initial RCPs; however, efforts to derive socioeconomic pathways consistent with each RCP are discussed in Chapter 20.

1.1.3.1. Comparison of RCP and SRES Scenarios

Whereas WGI AR5 is based primarily on results from the RCP CMIP5, the WGII AR5 also uses results from the SRES CMIP3, and thus identifies similar or parallel scenarios from each set. The radiative forcing from the SRES and RCP scenarios is compared in Figure 1-4a. For the latter half of the 21st century, SRES A1FI lies above all RCP and other SRES; SRES A2 has a similar trajectory to RCP8.5 with both reaching about 8 W m^{-2} by 2100; and SRES B1 approximately matches RCP4.5 with both leveling off at about 4 W m^{-2}. RCP6.0 starts similarly to both RCP4.5 and SRES B1, but after 2060 it increases to about 5 W m^{-2}. RCP2.6, a strong mitigation scenario with net CO_2 removal by 2100, falls well outside the SRES range B1 to A2, peaking at about 2.6 W m^{-2} in 2040 and dropping thereafter (WGI AR5 Figure 1-15, Tables AII.6.1 to AII.6.10).

Total RF does not adequately describe the differences in climate change between SRES and RCP scenarios. All RCPs adopted stringent air pollution mitigation policies and thus have much lower tropospheric ozone and aerosol abundances than the SRES scenarios, which ignored the role of air quality regulations (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of ozone and particulate matter precursor emissions, there is almost no overlap between SRES and RCP scenarios (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of surface ozone at the continental scale, after 2060 the RCPs are similar to low-end SRES B1 (WGI AR5 Tables AII.7.1 and AII.7.2).

Global mean surface temperature change for these scenarios is shown in Figure 1-4b, based on WGI AR5 (Chapters 11, 12; Tables AII.7.5 and AII.7.6) and WGI AR4 (Figure 10.26). For purposes here, that is, of understanding differences in impact studies using different scenarios, only model CMIP5 ensemble means are shown for the RCPs. If the standard deviation of the models were plotted, all RCPs would touch or overlap through the century (WGI AR5 Table AII.7.5), but even this range underestimates the uncertainties in temperature change for those scenarios (see WGI AR5 Chapter 12). The AR5 RCP data are taken directly from the CMIP5 runs, whereas the AR4 data are based on a simple model, parameterized to match the different CMIP3 models (see Figure 1-4 caption). In terms of temperature change, RCP8.5 is close to SRES A2, but below SRES A1FI. RCP4.5 follows SRES B2 up to 2060, but then drops to track SRES B1. RCP6.0 has lower temperature change to start, following SRES B1, but then increases toward SRES B2 by 2100. In general, scenarios SRES A1B, A1T, and B2 lie in the large gap between RCP8.5 and RCP4.5/6.0. The RCP2.6 temperature change stabilizes at about 1°C above the reference period (1986–2005). The other RCPS and all SRES scenarios span the range 1.8°C to 4.1°C for the 2090s. The CMIP5 reference period is about 0.6°C above earliest observing period 1850–1900 (WGI AR5 Chapter 2).

1.1.3.2. Shared Socioeconomic Pathways

Shared Socioeconomic Pathways (SSPs) are being generated (Arnell et al., 2011; Kriegler et al., 2012) to form more complete scenarios that link each RCP's climate path to a range of human development pathways. The SSPs include three elements: (1) storylines, which are descriptions of the state of the world; (2) IAM quantitative variables (such as population, gross domestic product (GDP), technology availability); and (3) other variables, not included in the IAMs, such as ecosystem productivity and sensitivity or governance index. With these elements a goal of the SSP effort is to characterize a global socioeconomic future for the 21st century as a reference for climate change analysis (O'Neill et al., 2012). Combined SSP–RCP scenarios are needed to support synthesis across all IPCC Working Groups and, particularly for WGII, to facilitate the use of new climate modeling results with impacts, adaptation, and vulnerability (IAV) research. Five basic SSPs have been proposed, representing a wide range of possible development pathways,

[4] The Coupled Model Intercomparison Project is an activity of the World Climate Research Programme's Working Group on Coupled Modelling. Climate model output from simulations of the past, present, and future climate archived mainly in 2005–2006 constituted Phase 3 of the Coupled Model Intercomparison Project (CMIP3). Similar climate simulations by an expanded set of models with a close off date of March 2013 are being used in AR5 and constitute Phase 5 of the project (CMIP5). CMIP3 used the SRES scenarios, and CMIP5 used the Reference Concentration Pathway (RCP) scenarios.

primarily at global or large regional scales. For each RCP it is expected that one or more SSP could lead to that climate path. Several chapters of this report refer to the SSPs in their discussion of analyses of future impacts and vulnerability. Chapter 20 (Section 20.6.1) describes SSPs in more detail, and Chapter 21 (Section 21.2.2) notes how the time lags in producing SSPs has limited the use of CMIP5–RCP scenarios in AR5.

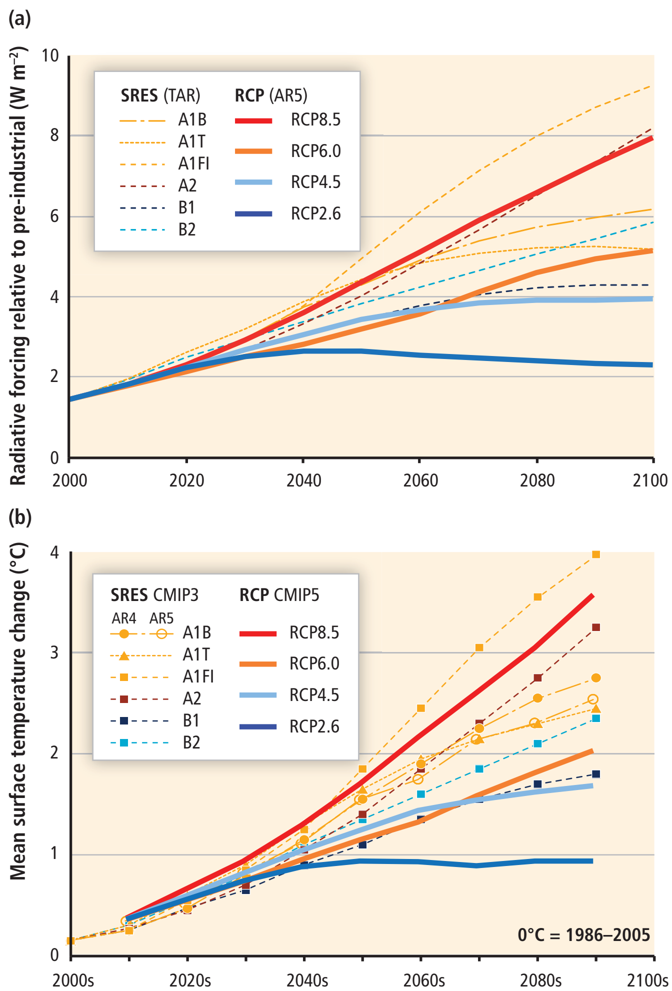


Figure 1-4 | (a) Projected radiative forcing (RF, W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century using the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the Third Assessment Report Appendix II (Table II.3.11). For RF derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, see WGI (Section 12.3; Tables AII.6.9, 6.10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8, and 7.6 W m^{-2} for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 W m^{-2} to match the RCPs at year 2000 because the climate change over the 21st century is driven primarily by the changes in RF and the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI AR5 Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016–2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See WGI AR5 Chapters 11, 12; Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (WGI AR4 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. For an assessment of uncertainties and *likely* ranges of temperature change, see WGI AR5 Figures 11.24, 11.25, 12.4, 12.5, 12.40.

1.1.4. Evolution of Understanding the Interaction between Climate Change Impacts, Adaptation, and Vulnerability with Human and Sustainable Development

The continuing increase in GHG emissions has highlighted the commitment to climate change and its varied impacts and has contributed to an increasing emphasis on vulnerability, adaptation, and sustainability. The possible range of socioeconomic trajectories in countries with low, medium, high, and very high human development is among the largest sources of uncertainty in scenario building and climate projections. A deeper understanding of development patterns, adaptation limits, and maladaptation, as well as options for more climate resilient pathways, has helped identify a larger range of potential climate change impacts and the risks they pose to society.

The first three WGII reports focused primarily on characterizing the biophysical impacts of climate change, with a progressively more elaborated understanding of economic and social impacts. The literature of the last decade indicates a more integrated understanding of the physical and social impacts of climate change. The extent and structure of WGII AR5 shows such advancements. The AR4 Synthesis Report asserted that "climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations" (IPCC, 2007d, p. 64). WGII AR4 Chapter 20 offered a catalog of multiple stresses jointly impacting people and communities and also highlighted questions of justice and equity in shaping development pathways in the context of climate change.

1.1.4.1. Vulnerability and Multiple Stressors

Climate-related risks interact with other biophysical and social stressors. Vulnerability is defined in the WGII TAR Glossary in terms of susceptibility and as a "function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity." Since then, the understanding of vulnerability has acquired increased complexity as a multidimensional concept, with more attention to the relation with structural conditions of poverty and inequality. WGII AR5 defines vulnerability simply as the propensity or predisposition to be adversely affected, and many chapters identify such vulnerabilities through societal risks, particularly in low-income economies. Recent studies suggest that climate impacts could slow down or reverse past development achievements; hinder global efforts on poverty reduction; and lead to human and environmental insecurity, displacement and conflict, maladaptation, and negative synergies (Jerneck and Olsson, 2008; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; Ogallo, 2010; see also Sections 3.5.1, 8.2.4, 12.2.1, 12.4.1, 12.5.1, 13.2.1, 14.7).

The concept of resilience emerged from ecological sciences and has been increasingly used by social sciences. In climate change literature it describes the ability of a system to respond to disturbances, self-organize, learn, and adapt (Turner, 2010; Brown, 2013; WGII AR5 Glossary). Vulnerability, adaptation, and resilience are determined by multiple stressors, a combination of biophysical and social factors that jointly determine the propensity and predisposition to be adversely affected. For example, adaptive capacity in many urban centers in less

Frequently Asked Questions

FAQ 1.3 | How has our understanding of the interface between human, natural, and climate systems expanded since the 2007 IPCC Assessment?

Advances in scientific methods that integrate physical climate science with knowledge about impacts on human and natural systems have allowed the new assessment to offer a more comprehensive and finer-scaled view of the impacts of climate change, vulnerabilities to those impacts, and adaptation options, at a regional scale. That's important because many of the impacts of climate change on people, societies, infrastructure, industry, and ecosystems are the result of interactions between humans, nature, and specifically climate and weather, at the regional scale.

In addition, this new assessment from Working Group II greatly expands the use of the large body of evidence from the social sciences about human behavior and the human dimensions of climate change. It also reflects improved integration of what is known about physical climate science, which is the focus of Working Group I of the IPCC, and what is known about options for mitigating greenhouse gas emissions, the focus of Working Group III. Together this coordination and expanded knowledge inform a more advanced and finer-scaled, regionally detailed assessment of interactions between human and natural systems, allowing more detailed consideration of sectors of interest to Working Group II such as water resources, ecosystems, food, forests, coastal systems, industry, and human health.

developed countries is constrained by poverty, unemployment, quality of housing, or lack of access to potable water, sanitation, health care, and education interacting with land degradation, water stress, or biodiversity loss (Sections 8.2.4, 11.6.2, 22.4.4). Adaptation options and limits for high-end warming scenarios are often contextualized in relation to socioeconomic vulnerabilities and other stressors (Gupta et al., 2010; New et al., 2010; Stafford Smith et al., 2011; Brown, 2012; World Bank, 2012; see also Section 16.4.2.4).

1.1.4.2. Adaptation, Mitigation, and Development

Impacts of climate change will vary across regions and populations, through space and time, dependent on myriad factors including non-climate stressors and the extent of mitigation and adaptation. Changes in both climate and development are key drivers of the core components of risk (exposure, vulnerability, and physical hazards). The relations with development are complex and contested. There is disagreement about fundamental issues, such as the compatibility of development goals and climate change mitigation, the prioritization of responses (reducing consumption versus investment in sustainable technologies), and the stage of development at which countries should take action (see Box 1-2 for terms used to characterize stages of development) (Schipper, 2007; Grist, 2008; Brooks et al., 2009). The literature points to how inequalities, trade imbalances, intellectual property rights, gender injustice, or agricultural systems, *inter alia*, cannot be addressed with development focusing solely on increasing economic growth (Pogge, 2008; McMichael, 2009; Alston, 2011; UNDP, 2007, 2011; Büscher et al., 2012; OECD, 2013).

The recent literature shows increasing attention to questions of ethics, justice, and responsibilities relating to climate change (Timmons and Parks, 2007; O'Brien et al., 2010; Pelling, 2010; Arnold, 2011; Gardiner, 2011; Caney, 2012; Marino and Ribot, 2012). As basic resources such as energy, land, food, or water become threatened, inequalities and unfairness may deepen, leading to maladaptation and new forms of vulnerability. Responses to climate change may have consequences and outcomes that favor certain populations or regions. For example, there are increasing cases of land-grabbing and large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities (Borras et al., 2011; see also Section 14.7). Ethical perspectives are also important in relation to adaptation constraints and limits (see Section 16.7) and mitigation (see Section 1.3.4 and WGIII AR5).

Climate change impacts have become a central issue in the work of developmental organizations such as the United Nations specialized agencies, bilateral donor institutions, and non-governmental organizations (NGOs) that link adaptation concerns with ongoing development efforts. The increase in adaptation literature and experience, however, has led to the development of adaptation policies in many parts of the world, as reflected in four chapters here devoted to adaptation (14 to 17) and all of the regional chapters of this report. At the policy level, individual country National Adaptation Programmes of Action and National Communication reports to the United Nations Framework Convention on Climate Change (UNFCCC) had in the past focused primarily on physical climate change drivers and impacts. An analysis of National Communications documents submitted through 2004 by many of the Annex 1 countries, for example, showed that climate change impacts and adaptation receive very limited attention relative to the discussion of GHG emissions and mitigation policies (Gagnon-Lebrun and Agrawala, 2006). However, concern and actual progress toward adaptation is evident in Latin America (Gutierrez and Espinosa, 2010) and in recent National Communications of some non-Annex 1 countries, such as India (2012) and Iran (2010), which devoted a substantive part of their recent reports to the topic of adaptation.

Some researchers and institutions have sought to identify a continuum between development, adaptation strategies, and financing, including increasing attention to co-benefits with mitigation (USAID, 2008; Heltberg et al., 2009; Mearns and Norton, 2010; World Bank, 2010; Richardson et al., 2011; OECD, 2013). "Greener" development and market-based mechanisms are being explored as instruments to achieve synergies

Box 1-2 | Country Development Terminology

There are diverse approaches for categorizing countries on the basis of their level of development and for defining terms such as industrialized, developed, or developing. Table 1-1 presents selected categorizations used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas (UN DESA, 2012). The United Nations Statistics Division specifies developed and developing regions based on "common practice." In addition, specific countries are designated as least developed countries, landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries (World Bank, 2013). The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) (UNDP, 2013).

Table 1-1 | Selected country development categorizations used in this report.

Categorization approach	Categories	Criteria	Reference
United Nations	• Developing regions • Developed regions	Common practice	UN DESA (2012)
	Least developed countries	• Gross National Income (GNI) per capita • Human assets • Economic vulnerability to external shocks	UN DESA (2008)
	Landlocked developing countries	• Lack of territorial access to the sea • Remoteness and isolation from world markets • High transit costs	UN (2003)
	Small island developing states	Low-lying coastal countries sharing similar socioeconomic and environmental vulnerabilities	UN (1993)
	Economies in transition/transition economies	Countries changing from central planning to free markets	UN DESA (2013)
World Bank	• Low income • Lower middle income • Upper middle income • High income	GNI per capita	World Bank (2013)
UNDP	• Low human development • Medium human development • High human development • Very high human development	• GNI per capita • Life expectancy at birth • Mean years of schooling • Expected years of schooling	UNDP (2013)

between mitigation and adaptation efforts, development financing, and planning, and links to energy needs are some of the instruments explored. Large concerns remain, however, about the preconditions needed for market mechanisms to work as intended, the problems of carbon leakage, and the potential negative effects of some mitigation strategies (Liverman, 2010; see also Section 13.1.3 and WGIII AR5 Chapter 15).

1.1.4.3. Transformation and Climate-Resilient Pathways

Transformation—a change in the fundamental attributes of a system including altered goals or values—has emerged as a key concept in describing the dimensions, types, and rates of societal response to climate change. In the context of adaptation, we can distinguish between incremental and transformative adaptation, the latter referring to changes in the fundamental attributes of a system in response to climate change and its effects (WGII AR5 Glossary; Park et al., 2012). The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) recognized transformation in technological, financial, regulatory, legislative, and administrative systems (IPCC, 2012; see Sections 1.3.1, 20.5). Recent literature points to changes in values, norms, belief systems, culture, and conceptions of progress and well-being as either facilitating or preventing transformation (Pelling, 2010; Stafford Smith et al., 2011; Kates et al., 2012; O'Brien, 2013). Transformation of this nature requires a particular understanding of risks, adaptive management, learning, innovation, and leadership, and may lead to climate resilient development pathways (see Section 1.2.3 and Chapter 20). Transformational change is not called for in all circumstances (Pelling, 2010) and in some cases may lead to negative consequences for some locations or social groups, contributing to social inequities (O'Brien, 2013). Climate resilient pathways include actions, strategies, and choices that reduce climate change impacts while assuring that risk management and adaptation can be implemented and sustained.

1.1.4.4. The Opportunity Space for Decision Making

Recognizing the need for policy-relevant science, much scientific activity tends to be coordinated through international programs that focus on, for example, biodiversity, desertification, food security, impacts on social practices and institutions, and monitoring sea level rise. The trend in research is to create synergies across the sciences by including social and human sciences perspectives and transdisciplinarity. The production of information with non-scientific sources such as indigenous knowledge or stakeholder views is also enriching climate change research. This trend has led to the merging of relevant global programs of the international councils for science and for social science (ICSU and ISSC) under the umbrella "Future Earth" (see also ISSC and UNESCO, 2013). This expanded scientific focus combined with increased practice and experience with adaptation creates a new opportunity space for evaluating policy options and their risks in the search for climate resilient development pathways (Figure 1-5) (Sections 2.1, 2.4.3, 20.2, 20.3.3). Human and social-ecological systems can build resilience through adaptation, mitigation, and sustainable development.

Over the next few decades, global temperatures are projected to increase along broadly similar pathways, whether or not mitigation of GHGs occurs (Section 1.3.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate and societal responses, including adaptation, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increases diverge across emissions scenarios. During this longer term era of climate options, near-term and ongoing mitigation efforts as well as development trajectories will determine the risks associated with climate change.

1.2. Major Conclusions of the Working Group II Fourth Assessment Report

This section presents highlights of the IPCC Fourth Assessment Report that are particularly relevant to AR5 as a point of departure. These highlights are drawn from the AR4 Synthesis Report, the WGII AR4

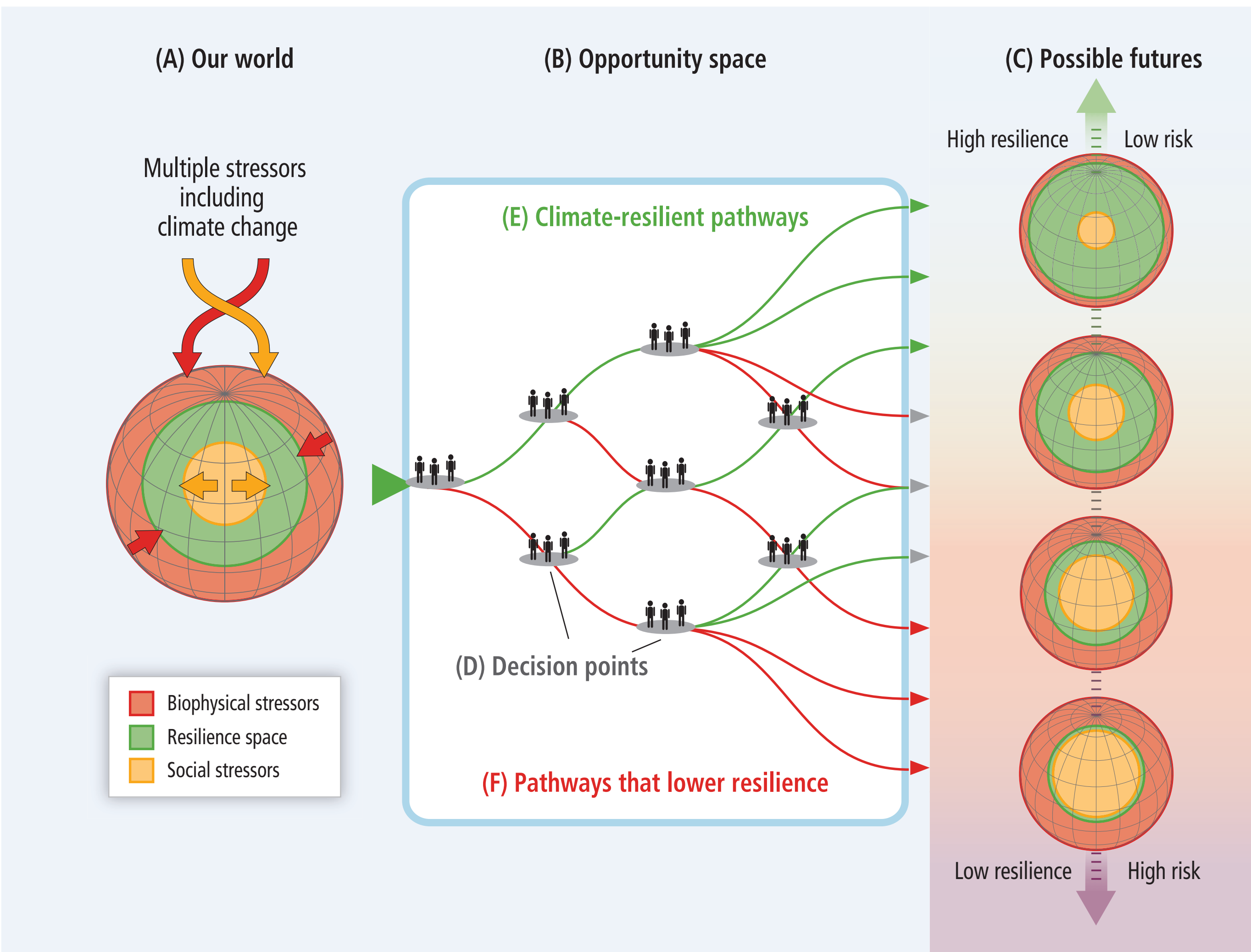


Figure 1-5 | Opportunity space and climate-resilient pathways. (a) Our world is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (b) Opportunity space refers to decision points and pathways that lead to a range of (c) possible futures with differing levels of resilience and risk. (d) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (e) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (f) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures.

Summary for Policymakers (SPM), and the WGII AR4 chapter Executive Summaries.

1.2.1. Observed Impacts

Evidence presented in WGII AR4 Chapter 1 indicated that physical and biological systems on all continents and in most oceans were being affected by recent climate changes, particularly regional temperature increases (Rosenzweig et al., 2007, p. 81). In terrestrial ecosystems, warming trends were consistent with observed change in the timing of spring events and poleward and upward shifts in plant and animal ranges. The authors found that the geographical locations of observed changes during the period 1970–2004 are consistent with spatial patterns of atmospheric warming. The types of hydrologic changes reported included effects on snow, ice, and frozen ground; the number and size of glacial lakes; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; thermal structure and water quality of rivers and lakes; and more intense drought and heavy rains in some regions. The authors concluded from a synthesis of studies "that the spatial agreement between regions of significant warming and the locations of significant observed changes is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems" (IPCC, 2007c, p. 9).

Observed regional impacts to human systems were less obviously attributed to anthropogenic climate change. AR4 authors concluded that **"There is *medium confidence* that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers"** (IPCC, 2007d, p. 3). They presented evidence on the effects of temperature increases on agricultural and forest management at Northern Hemisphere (NH) higher latitudes (e.g., earlier spring planting of crops, alterations in disturbance regimes of forests due to fires and pests); on some aspects of human health (e.g., heat-related mortality in Europe, changes in infectious disease vectors in some areas, and allergenic pollen in NH high and mid-latitudes); and some human activities in the Arctic (e.g., hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports).

The authors of AR4 concluded that "Recent climate changes and climate variations are beginning to have effects on many other natural and human systems. However, based on published literature, the impacts have not yet become established trends" (IPCC, 2007c, p. 9). Three examples were cited: in mountain regions melting glaciers enhanced risk of glacier lake outburst floods on settlements; in the Sahelian region of Africa warmer and drier conditions had detrimental effects on some crops; and in coastal areas sea level rise and human development contributed to losses of coastal wetlands and mangroves and to increases in damage from coastal flooding.

1.2.2. Key Vulnerabilities, Risks, and Reasons for Concern

In an effort to provide some insights into the seriousness of the impacts of climate change WGII TAR (Chapter 19) identified five "Reasons for Concern" (RFC) focusing on (1) unique and threatened systems, (2) extreme climate events, (3) distribution of impacts, (4) aggregate impacts, and (5) large-scale discontinuities (see Figure SPM-2 in IPCC, 2001b). Considering new evidence of observed changes on every continent, coupled with more thorough understanding of the concept of vulnerability, the AR4 concluded that the five "reasons for concern identified in the TAR remained a viable framework to consider key vulnerabilities" (IPCC, 2007d, p. 19).

The AR4 Synthesis Report SPM concluded with the following key message: **Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk** (IPCC, 2007d, p. 22). The concept of risk (the confluence of likelihood and consequence) is the focus of this AR5 Report. All chapters, especially 2, 18, and 19, now focus on climate change, related stressors, resulting vulnerabilities, and associated risks. Correlating the risk-based framing of the RFC in WGII AR5 with the conclusions reported in the AR4 SPM is straightforward (italics indicate new terms that have been added to the RFC definitions from the IPCC, 2007d, p. 19):

- Risks to Unique and Threatened Systems: "There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase."
- *Risks Associated with* Extreme Weather Events: "Responses to some recent extreme events reveal higher levels of vulnerability than the TAR. There is now higher confidence in the projected increases in droughts, heat waves, and floods, as well as their adverse impacts."
- *Risks Associated with the* Distribution of Impacts: "There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. Moreover, there is increased evidence that low-latitude and less developed areas generally face greater risk, for example, in dry areas and megadeltas."
- *Risks Associated with* Aggregate Impacts: "Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming."
- Risks Associated with Large-Scale Discontinuities: "There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales."

WGII AR5 Chapters 18 and 19 recognize new evidence about the RFC in the context of risk. Chapter 18 expands our understanding of how observed and attributed impacts, vulnerabilities, and associated risks support the identification of the dependence of the RFC on temperature "up to the present." Chapter 19 extends this analysis to future temperatures. Both chapters demonstrate how accounting for both components of risk in assessing the RFC permits a clearer understanding of "key vulnerabilities."

1.2.3. Interaction of Adaptation and Mitigation in a Policy Portfolio

A conclusion of AR4 is that coping with risks of climate change will involve a portfolio of initiatives that will evolve iteratively over time as new information about the workings of the climate system and new insights into how various responses are actually working and penetrating the global socioeconomic structure. The WGII AR4 concluded that (1) neither adaptation nor mitigation alone can avoid all climate change impacts, though together they can significantly reduce the risks of climate change; (2) adaptation is necessary in the short and longer term to address impacts, even for the lowest stabilization scenarios assessed, but there are barriers, limits, and costs, though these are not fully understood; (3) unmitigated climate change would *likely* exceed the adaptive capacity of natural, managed, and human systems in the long term; and (4) while many impacts can be reduced, delayed, or avoided by mitigation, delayed emission reductions "significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts." (IPCC, 2007d, p. 19).

WGII AR5 devotes considerable attention to the interface of adaptation and mitigation and the mechanisms for iterating decisions as described in a collection of chapters (16, 17, 19, and 20) designed explicitly for this purpose. These chapters build substantially upon key messages from the AR4 chapter entitled "Inter-relationships between adaptation and mitigation" (IPCC, 2007b, p. 747), including:

- Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation unavoidable.
- Without mitigation, a magnitude of climate change is likely to be reached that makes adaptation impossible for some natural systems, while for most human systems it would involve very high social and economic costs.
- **"Creating synergies between adaptation and mitigation can increase the cost-effectiveness of actions and make them more attractive to stakeholders, including potential funding agencies (medium confidence)."** Such synergies, however, provide no guarantee that resources are used in the most efficient manner and opportunities for synergies are greater in some sectors (e.g., agriculture and forestry) than others (e.g., energy, health, and coastal systems).
- **"It is not yet possible to answer the question as to whether or not investment in adaptation would buy time for mitigation (high confidence)."** Barriers to understanding the trade-offs of the immediate benefits of localized adaptation and the longer term global benefits of mitigation, coupled with the limitation of models to simulate the intricacies of the interactions of the two, present a challenge to designing and implementing an "optimal mix" of response strategies.
- **"People's capacities to adapt and mitigate are driven by similar sets of factors (high confidence).** These factors represent a generalized response capacity that can be mobilized for both adaptation and mitigation." The authors noted that even societies with high adaptive capacity can be vulnerable to climate change, variability, and extremes.

1.3. Major Conclusions of More Recent IPCC Reports

Since publication of the AR4 in 2007, the IPCC has produced two Special Reports: the *Special Report on Renewable Energy Sources and Climate Change Mitigation*, produced by Working Group III and published in 2011; and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, produced jointly by WGI and WGII and published in 2012. In addition, the AR5 cycle has staggered the assessment work for its three working groups. WGI AR5 was released in September 2013, and WGIII AR5 will be published after WGII AR5 in 2014. In this section we summarize the major conclusions of the SREX, the SRREN, WGI AR5, and preliminary findings from WGIII AR5. We focus on the key findings, framings, and conceptual innovations these reports bring to WGII AR5.

One common theme that cuts across the Working Groups is the connection of three basic elements of climate change: (1) detection of climate change or its impacts; (ii) attribution of that observed climate change to the increases in GHGs (i.e., human cause, WGI) or attribution of local impacts to the observed climate change in that region; and (3) projection of these impacts and climate change into the 21st century. Table 1-2 gives a summary of phenomena for which such detection,

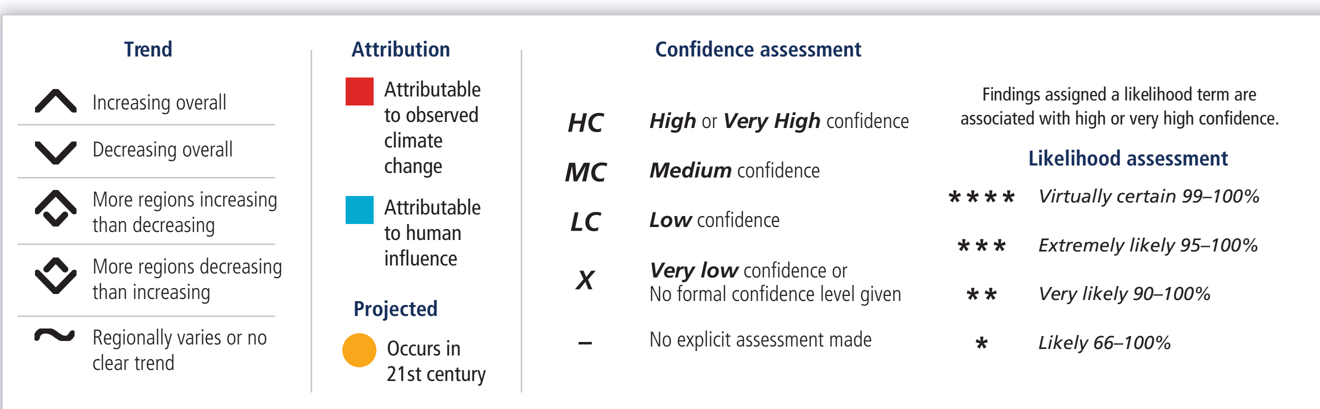


Table 1-2 | Confidence in the observation, attribution, and projection of changes in climate system phenomena.

	Phenomenon	Change	Observed to 2010 (X-axis, Figure 1-6)	Y-axis, Figure 1-6: Attribution	Y-axis, Figure 1-6: Projected 2050-2100	Source
1	Greenhouse gases: CO_2, CH_4, N_2O	∧	****	**** ■ (blue)	**** (RCPs: CO_2,N_2O) ●	AR5 I-2, I-10, I-11, I-12
2	Global Mean Surface Air Temperature (GMST)	∧	****	*** ■ (blue)	**** ●	AR5 I-2, I-10, I-11, I-12
3	GMST over all continents except Antarctica	∧	****	* ■ (blue)	**** ●	AR5 I-2, I-10, I-11, I-12
4	Global mean sea level	∧	****	** ■ (blue)	**** ●	AR5 I-3, I-10, I-13
5	Arctic sea ice cover	∨	****	** ■ (blue)	** ●	AR5 I-4, I-10, I-11, I-12
6	Hot days and nights over land (warmth, frequency)	∧	**	** ■ (blue)	**** ●	AR5 SPM-1
7	Cold days and nights over land (warmth, frequency)	∨	**	** ■ (blue)	**** ●	AR5 SPM-1
8	Extreme high sea level (incidence, magnitude)	∧	* (since 1970)	X	** ●	AR5 SPM-1
9	Heat waves and warm spells over land (frequency, duration)	◇	*MC*	* ■ (blue)	** ●	AR5 SPM-1
10	Heavy precipitation events	◇	*	*MC* ■ (blue)	** ●	AR5 I-2, I-10, I-12
11	Drought (intensity, duration)	◇	*MC* (some regions)	*LC* ■ (blue)	* ●	AR5 SPM-1, SREX-4
12	Tropical cyclones (intensity, frequency, some basins)	~	*LC*	*LC* ■ (blue)	MC (intensity increase, some basins) ●	AR5 SPM-1
13	Global mean precipitation	∧	*LC*	*LC* ■ (blue)	**** ●	AR5 I-2, I-10, I-11, I-12
14	Contrast between wet and dry regions	∧	X	X	HC ●	AR5 I-12
15	Snow cover (Northern Hemisphere, extent)	∨	HC	HC ■ (blue)	HC ●	AR5 I-4, I-10, I-12
16	Permafrost regions (degrade)	∨	MC	X	MC ●	AR5 I-4, I-12
17	Storm tracks (shift poleward)	∧	*	X	* ●	AR5 I-2, I-12
18	Wave heights (different oceans)	∧	MC (N. Atlantic)	X	** (Arctic a) * (Southern b) ●	AR5 I-3, I-13
19	Upper ocean (warming)	∧	****	*** ■ (blue)	*** ●	AR5 I-3, I-10, I-11, I-12
20	Ocean acidification	∧	****	*** ■ (blue)	**** ●	AR5 I-3, I-10, I-6
21	Oceanic oxygen	∨	*MC*	*MC* ■ (blue)	** ●	AR5 I-3, I-10, I-6
22	Floods (magnitude, frequency)	~	*LC*	*LC* ■ (blue)	*LC* ●	SREX-3
23	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	∧	*HC*	*HC* ■ (blue)	*HC* ●	SREX-3, AR4 SyR
24	Monsoons	~	*LC*	*LC* ■ (blue)	*LC* ●	SREX-3
25	Plant and animal species (move poleward or up in altitude)	∧	*HC*	*HC* ■ (red)	*HC* ●	AR4 II-SPM, AR4-SyR
26	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	∧	*HC*	*HC* ■ (red)	*HC* ●	SREX-3, AR4 SyR
27	Timing of spring events (earlier leafing, greening, planting, bird migration, etc.)	∧	*HC*	*HC* ■ (red)	*HC* ●	AR4 SyR
28	Marine/freshwater biological systems (shifts in algal, plankton, and fish ranges)	~	*HC*	*HC* ■ (red)	*HC* ●	AR4 SyR
29	Human health (heat-related mortality, infectious disease vectors)	∧	*MC*	MC ■ (red)	X ●	AR4 SyR
30	Water resources	∨	X	X	*HC* (many regions) ●	AR4 SyR-SPM
31	Mountain glaciers	∨	*HC*	X	*HC* ●	AR4 II-SPM
32	Coral degradation, bleaching	∧	*HC*	–	*HC* ●	AR4 II-SPM, SyR-SPM
33	Economic losses from weather- and climate-related disasters	∧	*HC*	X	*HC* ●	SREX-4
34	Annual costs of climate change	∧	X	X	** ●	AR4 SyR-SPM

Figure 1-6 | Confidence in the attributed (squares) and projected 21st century (yellow circles) changes in climate system phenomena plotted as a function of confidence in their detection to date. Phenomena and sources (AR4, SREX, WGI AR5) are given in Table 1-2. Strength of confidence is sorted into the nine bins as noted on the axes (no assessment was made; a statement was made and assigned no formal confidence level or *very low confidence*; *low confidence*; *medium confidence; high confidence* (no quantification); or *likely; very likely; extremely likely; virtually certain*). Attribution is to either human influence (blue squares, as used by WGI) or observed local/regional climate change (red squares, as used by WGII). Projections assume global warming exceeding 2°C. For AR5 WGII results see, *inter alia*, Chapters 18 and 19.

attribution, or projection has been made across the Working Groups. A schematic presentation of this detection–attribution–projection sequence from preceding reports is given in Figure 1-6. For WGII AR5 attributions, see Chapter 18; and for projections, see the other chapters.

1.3.1. Special Report on Renewable Energy Sources and Climate Change Mitigation

SRREN (IPCC, 2011) assesses literature on the challenges of integrating renewable energy sources into existing energy sources to meet the goals of climate change mitigation and sustainable development. More specifically, it examines six renewable energy sources (bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy) in terms of available technologies, technological potential, and associated costs. SRREN found that the deployment of renewable energy technologies has increased rapidly in recent years, often associated with cost reductions that are expected to continue with advancing technology. Despite the small contribution of renewable energy to current energy supplies, SRREN shows the global potential of renewable energy to be substantially higher than the global energy demand. It is therefore not the technological potential of renewable energy that constrains its development, but rather economic factors, system integration, infrastructure constraints, public acceptance, and sustainability concerns

Table 1-3 | Examples of linkages between the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and the AR5 WGII with chapter references in parentheses.

	SRREN findings	WGII AR5 findings
Water resources	Water availability limits the development of water cooled thermal power and hydropower. Environmental issues will continue to affect hydropower opportunities. (5.1, 5.6, 9.3)	Climate change is predicted to affect surface and groundwater supplies. Development of water-dependent energy resources can also affect freshwater ecosystems. (4.4, 19.3)
Ocean systems	Most ocean energy technologies are at the conceptual phase. Potential technologies include submarine turbines for tidal currents, ocean thermal energy conversion, and devices that harness energy of waves and salinity gradients. (6.2, 6.3, 6.5)	Offshore renewable energy introduces additional drivers of change for near- and offshore coastal and marine ecosystems and species. Ocean geoengineering approaches may have large environmental footprints. (5.5, 6.4)
Land cover changes	The sustainability of bioenergy (i.e., lifecycle GHG emissions) is influenced by land and biomass resource management practices. (2.2, 2,8, 9.3)	Land cover change associated with biofuel production has food security implications; related land use change can alter ecosystems, species, and carbon storage. (19.3, 19.4, 27.2)
Resilient pathways	Higher energy prices associated with transitions from fossil fuels to biofuels and other renewable energy sources may have adverse effects on socioeconomic development. (9.4, 10.5)	The challenge is to identify and implement mixes of technological options that reduce net carbon emissions and support sustained economic and social growth. (20.3)
Regional effects	Latin America is second to Africa for technical potential in producing bioenergy from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands. (2.2)	Bioenergy production requires large areas with risk of environmental degradation and may involve strong economic teleconnections (e.g., Latin America). (27.2, 27.3)
	The quantity of water resources availability in Central and South America is the largest in the world. The region has the largest proportion of electricity generated through hydropower facilities. (5.2)	Hydropower, the main source of renewable energy available in Central and South America, is prone to serious effects of climate change. Altered river flows affect development in this region and use of land for biofuel production. (27.3, 27.6, 27.8)

(IPCC, 2011). Several SRREN findings have clear linkages with this assessment of climate change impacts, adaptation, and vulnerability, as summarized in Table 1-3.

1.3.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

SREX (IPCC, 2012) is the first IPCC Special Report produced jointly by Working Groups I and II and is the first IPCC report focused specifically on risk management. The report integrates perspectives from historically distinct research communities studying climate science, climate impacts, extreme events and impacts, climate adaptation, and disaster risk management. It assesses relationships between climate change and the characteristics of extreme weather and climate events. SREX provides information on existing societal exposure and vulnerability to climate-related extreme events and disasters; observed trends in weather- and climate-related disasters, disaster losses, and in disaster risk management; projected changes in weather and climate extremes during the 21st century; approaches for managing the increasing risks of climate extremes and disasters; and implications for sustainable development. SREX Chapter 9 is devoted to 14 case studies that illustrate the impacts of extreme climate-related events and options for risk management and adaptation, such as early-warning systems, new forms of insurance coverage, and expansion of social safety nets.

1.3.2.1. Themes and Findings of Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The most relevant results of the SREX assessment follow. They are synthesized along these major themes: changing weather and climate-related extreme events, trends in disaster losses, and managing the risks of extreme events and disasters. Other examples of findings presented in SREX concerning the type, magnitude, and frequency of extreme weather and climate events are presented in Table 1-2 of this chapter.

- Based on observations since 1950 there is evidence of changes in some climate-related extremes. It is *very likely* that there has been an overall decrease in the number of cold days and nights, and increase in the number of warm days and nights, at the global scale (SREX SPM, Section 3.3.1, Table 3-2). It is *likely* that there has been an increase in extreme coastal high water events related to increases in mean sea level (SREX SPM, 3.5.3). It is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale (SREX SPM, Sections 3.2.2, 3.3.1, 3.3.2, 3.4.4, 3.5.3, Table 3-1).
- The models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas (SREX SPM, Sections 3.3.2, 3.3.4, Table 3-3, Figure 3-5).
- It is *likely* that the frequency of heavy precipitation will increase in the 21st century over many areas of the globe (SREX SPM, Sections 3.3.2, 3.4.4, Table 3-3, Figure 3-7).
- Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement*, *medium evidence*) (SREX SPM, Sections 4.5.1, 4.5.3, 4.5.4). Trends in losses have been heavily influenced by increasing exposure of people and economic assets (*high confidence*) (SREX SPM, Section 4.5.3).
- Economic, including insured, disaster losses associated with weather, climate-related events, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of GDP are higher in developing countries (*high confidence*). Deaths from natural disasters occur much more in developing countries. From 1970 to 2008, for example, more than 95% of deaths from natural disasters were in developing countries (SREX SPM, Sections 4.5.2, 4.5.4).
- Development practice, policy, and outcomes contribute to shaping disaster risks (*high confidence*): skewed development that may lead to environmental degradation, unplanned urbanization, failure of governance, or reduction of livelihood options result in increased

exposure and vulnerability to disasters (SREX SPM, Sections 1.1.2, 1.1.3, 2.2.2, 2.5).

- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (*robust evidence*, *high agreement*) (SREX SPM, Sections 5.2.3, 8.4.1, 8.5.2).
- Socioeconomic, demographic, health-related differences, access to livelihoods, good governance, and entitlements are some of the factors that lead to inequalities between people and countries. Inequalities influence local coping and adaptive capacity and pose challenges for risk management systems from local to national levels (*high agreement*, *robust evidence*) (SREX SPM, Sections 5.5.1, 6.2, 6.3.2, 6.6).
- The incorporation of climate change adaptation and disaster risk management into local, national, and international development practices and policies could bring benefits (*medium evidence*, *high agreement*) (SREX SPM, Sections 5.4, 5.5, 5.6, 6.3.1, 6.3.2, 6.4.2, 6.6, 7.4).
- Combining local knowledge with scientific and technical expertise helps communities reduce their risk and adapt to climate change (*robust evidence*, *high agreement*). Risk management works best when tailored to local circumstances (SREX SPM, Section 5.4.4).
- Many measures for managing current and future risks have additional benefits, such as improving peoples' livelihoods, conserving biodiversity, and improving human well-being (*medium evidence*, *high agreement*) (SREX SPM, Section 6.3.1, Table 6-1).
- Many measures, when implemented effectively, make sense under a range of future climates. These "low regrets" measures include systems that warn people of impending disasters; changes in land use planning; sustainable land management; ecosystem management; improvements in health surveillance, water supplies, and drainage systems; development and enforcement of building codes; and better education and awareness (SREX SPM, Sections 5.3,1, 5.3.4.3, 6.3.1, 6.5.1, 6.5.2, 7.4.3, Case Studies 9.2.11, 9.2.14).
- An iterative process involving monitoring, research, evaluation, learning, and innovation can promote adaptive management and reduce disaster risk in the context of climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6.3, 8.7).
- Actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6, 8.6.3, 8.7).

1.3.2.2. Advances in Conceptualizing Climate Change Vulnerability, Adaptation, and Risk Management in the Context of Human Development

SREX conceptual framing reflects the diversity of expert communities involved in the assessment. It links exposure and vulnerability with socioeconomic development pathways as determinants of impacts and disaster risk for both human society and natural ecosystems. It is important to note that SREX acknowledges the fundamental role that values and aspirations play in people's perception of risk, of change and causality, and of imagining present and future situations. This value-based approach is put to work as a tool for managing the risks of extreme events and disasters enabling the recognition that socioeconomic systems are in constant flux, and that there are many conflicting and contradictory values in play. The conceptual framing of the problem space offered by SREX (SREX Figure SPM 1-1) serves as a point of departure for many WGII AR5 chapters. Equally important is the conceptualization of a feasible solution space offered in SREX. The solution space is further refined in the WGII AR5 through emphasis on co-benefits of adaptation and mitigation and the further development of transformational change to enable climate resilient development.

1.3.3. Relevant Findings from IPCC Working Group I Fifth Assessment Report

This section is a WGII synthesis of the WGI AR5 report that focuses on topics relevant to WGII science.[5] The relevant WGI AR5 chapters and sections are denoted in parentheses. Where statements have *high confidence* or *likely* or better quantification, these qualifiers are dropped for readability. Likewise, many phrases are exact quotations but are not presented in quotes. An overall assessment of climate change over the last several decades from WGI is: Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. Human influence on the climate system is clear; it has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (SPM).

Greenhouse gases and climate forcing. Human activities are the dominant cause of the observed increase in well mixed GHGs since 1750 and of the consequent increase in climate forcing. The GHGs and their forcing continued to increase since AR4 (2, 6, 8). Ozone and stratospheric water vapor also contribute to this forcing (8). Aerosols partially offset this forcing and dominate the uncertainty in determining total anthropogenic forcing of climate change (8). Total anthropogenic climate forcing is positive and has increased more rapidly since 1970 than during prior decades (8). Present-day (2011) abundances of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) exceed the range over the past 800,000 years found in ice cores (5, 6). Annual emission of CO_2 from fossil fuels and cement production was 9.5 GtC in 2011, 54% above the 1990 level (SPM). More than 20% of added CO_2 will remain in the atmosphere for longer than 1000 years (6). Anthropogenic land use change has increased the land surface albedo (a negative forcing) and has also affected climate through the hydrologic cycle, but these effects

[5] This narrative is taken primarily from the executive summaries of the WGI Final Draft chapters and reflects the WGI SPM approved on 27 September 2013 in Stockholm. For the most part, WGI findings summarized here have *high confidence* or a *likely* or better quantification, and hence the confidence and likelihood statements have been dropped for readability. All quantitative ranges are *likely* (66% confidence) or *very likely* (90% confidence) or the modeled range (where noted). In a few instances, assessments with *low confidence* are included and so noted. This WGII narrative is intended to be accurate, but for the purpose here the exact WGI language has been edited and concatenated where possible (e.g., 1950 is substituted for "the middle of the 20th century"). Although quotation marks are not used, there remain long phrases that are direct quotes from the WGI AR5 chapters. All numerical values are verbatim. For the level of uncertainty and the precise wording of the WGI assessment refer directly to the WGI approved SPM and the accepted chapters.

are more uncertain and difficult to quantify (8.3.5). Spatial gradients in forcing (i.e., aerosols, ozone, land use change) affect regional temperature responses (8). Cumulative CO_2 emissions from 1750 to 2011 are 365 GtC (fossil fuel and cement) plus 180 GtC (deforestation and other land use change) (SPM). This 545 GtC represents about half of the 1000 GtC total that can be emitted and still keep global warming under 2°C relative to the reference period 1861–1880 (SPM).

Air quality on continental scales. Future surface ozone (air pollution) decreases over most continents for RCP2.6, RCP4.5, and RCP6.0; but it increases for RCP8.5 due to rising CH_4 (11). Changes in air quality for the RCPs are driven primarily by pollutant emissions and secondarily by climate change (11). Air pollution is less under RCP scenarios than under SRES scenarios (11).

Surface Temperatures. Global mean surface temperature increased by 0.85°C (0.65°C to 1.06°C) over the period 1880–2012 (linear trend) (SPM) and by 0.72°C over the period 1951–2012 (2). Each of the last 3 decades (from 1983 to 2012) has been successively warmer than any preceding decade since 1850 (SPM). The decade 2003–2012 has been the warmest over the instrumental record, even though the rate of warming over 1998–2012 is smaller than the average rate since 1951 (0.05°C vs. 0.12°C per decade) (2). For the NH, the period 1983–2012 was the warmest of the last 1.400 kyr (5). The slower surface warming trend over the period 1998–2012 vs. 1951–2012 is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal, possibly oceanic variability (SPM). Models reproduce the overall 1951–2012 warming trend, but not the smaller trend for 1998–2012 (9). More than half of the 1951–2010 temperature increase is due to the observed anthropogenic increase in GHGs (10). The projected near term (2016–2035) mean surface temperature increase is 0.9°C to 1.3°C (11), and the long term (2081–2100) ranges from 0.9°C to 2.3°C (RCP2.6) to 3.2°C to 5.4°C (RCP8.5) (values are relative to 1850–1900, the earliest period for which global mean surface temperatures have been measured, and include the 0.6°C offset from that period to the model reference period 1986–2005) (SPM, 2, 12).

Global temperatures during the last interglacial period (about 120,000 years ago) were never more than 2°C higher than preindustrial levels (5). By 2050 the global warming range is 1.5°C to 2.3°C above the 1850–1900 period based on the range across all RCPs and models (11.3.6). Near the end of the century (2081–2100) warming above 4°C is typical of RCP8.5, while that of RCP2.6 remains below 2°C (12). Orbital forcing will not trigger widespread glaciation during the next 1000 years (5).

Climate models reproduce observed continental-scale mean surface temperature patterns; on sub-continental and smaller scales model capability is reduced, but is better than in AR4 (9). Regional downscaling provides climate information at the smaller scales needed for impact studies and adds value in regions with highly variable topography and for various small-scale phenomena (9). Anthropogenic warming in the 21st century will proceed more rapidly over land areas than over oceans, and the Arctic region is projected to warm the most (11, 12).

Precipitation. Observed trends in global land-average precipitation have *low confidence* prior to 1950 and *medium confidence* thereafter (2). Simulation of large-scale precipitation patterns has improved somewhat since AR4, but precipitation at regional scales is not well simulated (9). Precipitation (global annual averages) will increase as temperatures increase, and the contrast between dry and wet regions and that between wet and dry seasons will increase over most of the globe (12). By 2100 under RCP8.5, high latitudes will experience more precipitation; many moist mid latitude regions will also experience more; while many mid-latitude and subtropical arid and semi-arid regions will experience less (12). These patterns are also typical of near-term climate change (11). Trends will not be apparent in all regions, especially in the near term, because of natural variability and possible influences of aerosols and land use change (11).

Extreme temperatures and precipitation. Since 1950, the numbers of cold days/nights have decreased and the numbers of warm days/nights have increased globally (2); and model simulation of these extreme events has improved since AR4 (9). Since 1950, anthropogenic forcing has contributed to the observed changes in daily temperature extremes on the global scale (10). In most regions the frequency of warm days/nights will increase in the next decades, while that of cold days/nights will decrease (11). Increases in the frequency, duration, and magnitude of hot extremes along with heat stress are expected; however, occasional cold winter extremes will occur (12). Extreme high temperatures (20-year return values) are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions (12). There is a *no confidence* level assigned to projected near-term increases in the duration, intensity, and spatial extent of heat waves and warm spells (11), but in the long term heat waves will occur at higher frequency and longer duration in response to increased seasonal mean temperatures (12.4.3). Since 1950, the frequency or intensity of heavy precipitation events has increased in North America and Europe (2, SPM). Trends in small-scale severe weather events (e.g., hail, thunderstorms) have *low confidence* (2). With global warming, the frequency and intensity of heavy/extreme precipitation events will increase over most mid-latitude land and over wet tropical regions (12), and extreme daily precipitation rates will increase faster than the mean time average (7). Most models underestimate the sensitivity of extreme precipitation to temperature variability/trends, and thus projections may underestimate these extremes (9).

Floods and droughts. In many regions, historical droughts (last 1000 years) and historical floods (last 500 years) have been more severe than those observed since 1900 (5). Global-scale trends in drought or dryness since 1950 have *low confidence* due to lack of direct observations, methodological uncertainties, and geographical inconsistencies; hence confidence levels in global drought trends since the 1970s as reported in AR4 are overstated (2). Regional trends are found: the frequency and intensity of drought has increased in the Mediterranean and West Africa, and it has decreased in central North America and northwest Australia since 1950 (2, 2.6.2.2). There is *low confidence* in attributing drought changes to human influence (10). Projected changes in soil moisture and surface runoff have low confidence in the near term (11), but by 2100 under RCP8.5, annual runoff will decrease in parts of southern Europe, Middle East, and southern Africa, and increase in high northern latitudes (12). Decreases in soil moisture with increased risk of agricultural drought are projected in presently dry regions (12).

Tropical cyclones, storms, and wave heights. Observed changes in tropical cyclone activity on a centennial scale as well as attribution to human influence have *low confidence* (2, 10); however, the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (2). In a few studies, high-resolution atmospheric models have reproduced the year-to-year variability of Atlantic hurricane counts (9). Future changes in intensity and frequency of tropical cyclones will vary by region, but basin-specific projections have *low confidence* (11, 14). The maximum wind speed and precipitation rates of tropical cyclones will increase (14).

Atmospheric circulation features have moved poleward since the 1970s, including a poleward shift of storm tracks and jet streams (2), and model simulation of these patterns has improved since AR4 (9). Large-scale trends in storminess over the last century have *low confidence* (2, 2.6.4). Projections of the position and strength of NH storm tracks, especially for the North Atlantic basin, have *low confidence* (11, 12, 14). With global warming, a shift to more intense individual storms and fewer weak storms is projected (12).

Mean significant wave height has increased over much of the Atlantic Ocean north of 45°N since 1950, with winter season trends of up to 20 cm per decade (*medium confidence*) (3, 3.4.5). Wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea ice extent (13). Wave heights will increase in the Southern Ocean as a result of enhanced wind speeds (13).

Ocean warming, stratification, and circulation. Overall, the ocean has warmed throughout most of its depth over some periods since 1950, and this warming accounts for about 93% of the increase in the Earth's energy inventory between 1971 and 2010 (3). The upper ocean above 700 m has warmed from 1971 to 2010, and the thermal stratification has increased by about 4% above 200 m depth (3). Anthropogenic forcings have made a substantial contribution this upper ocean warming (10). Measurement errors in the temperature data sets have been corrected since the AR4 (10). The global ocean continues to warm in all RCP scenarios (11, 12). To date there is no observational evidence of a long-term trend in Atlantic Meridional Overturning Circulation (3); and over the 21st century it is projected to weaken but not undergo an abrupt transition or collapse (12).

Ocean acidification and low oxygen. Oceanic uptake of anthropogenic CO_2 results in gradual acidification of the ocean (3). Since 1750 the pH of seawater has decreased by 0.1 (a 26% increase in hydrogen ion concentration) (3). Increased storage of carbon by the oceans over the 21st century will increase acidification, decreasing pH further by 0.065 for RCP2.6 and 0.31 for RCP8.5 (6). Aragonite under-saturation becomes widespread in parts of the Arctic and Southern Oceans and in some coastal upwelling systems at atmospheric CO_2 levels of 500 to 600 ppm (6). Oxygen concentrations have decreased since the 1960s in the open ocean thermocline of many regions (*medium confidence*) (3). By 2100, the oxygen content of the ocean will decrease by a few percent (6). There is no consensus on projection of the very low oxygen (hypoxic or suboxic) waters in the open ocean (6).

Sea ice. Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased at rate of 3.5 to 4.1% per decade between 1979 and 2012 (4). Over the past 3 decades, Arctic summer sea ice retreat was unprecedented and Arctic sea surface temperatures were anomalously high, compared with the last 1450 years (SPM). The Arctic average winter sea ice thickness decreased between 1980 and 2008 (4). Current climate models reproduce the seasonal cycle and downward trend of Arctic sea ice extent (9). Anthropogenic forcings have contributed to Arctic sea ice loss since 1979 (10). With global warming, further shrinking and thinning of Arctic sea ice cover is projected, and the Arctic Ocean will be nearly ice free in September before 2050 for the high-warming scenarios like RCP8.5 (11, 12). There is little evidence in climate models of an Arctic Ocean tipping point, that is, the transition from a perennially ice covered to a seasonally ice-free expanse beyond which further sea ice loss is unstoppable and irreversible (12). Annual Antarctic sea ice extent increased by 1.2 to 1.8% per decade between 1979 and 2012 (4). The scientific understanding of this observed increase has *low confidence* (10). With global warming, Antarctic sea ice extent and volume is expected to decrease (*low confidence*) (12).

Ice sheets, glaciers, snow cover, and permafrost. During periods over the past few million years that were globally warmer than present, the Greenland and West Antarctic ice sheets were smaller (5). The Antarctic and Greenland ice sheets have on average lost ice during the last 2 decades, and the rate of loss has increased over the most recent decade to a sea level rise equivalent of 0.6 mm yr^{-1} for Greenland and 0.4 mm yr^{-1} for Antarctica (4). Anthropogenic influences have contributed to Greenland ice loss since 1990 and to the retreat of glaciers since the 1960s, but there is *low confidence* in attributing the causes of Antarctic ice loss (10). With global warming, model studies agree that the Greenland ice sheet will significantly decrease in area and volume, while the Antarctic ice sheet increases in most projections (*confidence* not assessed) (12, 13.4.4). Global warming above a certain threshold (e.g., 2°C to 4°C above the 1850–1900 period) would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed) (13). There is *low confidence* and little consensus on the likelihood of abrupt or nonlinear changes in components of the climate system over the 21st century (12).

Multiple lines of evidence support very substantial Arctic warming since the mid-20th century (SPM). Almost all glaciers world-wide have continued to shrink since AR4 (4). Over the last decade, most ice was lost from glaciers in the Canadian Arctic, Greenland ice sheet periphery, Southern Andes, Asian Mountains, and Alaska (4). Current glacier extents are out of balance with current climate, and glaciers will continue to shrink even without further warming (4). Snow cover extent has decreased in the NH, particularly in spring (4); and reductions since 1970 have an anthropogenic component (10). Permafrost temperatures have increased in most regions since the early 1980s: observed warming was up to 3°C in parts of Northern Alaska and 2°C in parts of the Russian European North (4, SPM). With global warming, NH snow cover extent and permafrost extent will decrease further (11, 12). By 2100 the decrease in near-surface permafrost area ranges from 37% (RCP2.6) to 81% (RCP8.5) (*medium confidence*) (12).

Sea level rise. During the last interglacial period, when global mean temperatures were no more than 2°C above pre-industrial values (*medium confidence*), maximum global mean sea level was, for several thousand years, 5 m to 10 m higher than present (SPM, 5, 5.3.4, 5.6.1, 5.6.2, 13, 13.2.1) with substantial contributions from Greenland and Antarctic Ice Sheets (5, 13). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous 2 millennia (SPM). Global mean sea level has risen at an average rate of 1.7 mm yr^{-1} from 1901 to 2010 and at a faster rate, 3.2 mm yr^{-1}, from 1993 to 2010 (3). There is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s (10). The rate of global mean sea level rise during the 21st century will exceed that observed during 1971–2010 for all RCP scenarios (13). For the period 2081–2100 compared to 1986–2005, process-based models project a global mean sea level rise ranging from 0.26 to 0.55 m (RCP2.6) up to 0.45 to 0.82 m (RCP8.5) (13). By 2100 for RCP8.5, this rise is 0.52 to 0.98 m, with a rate of rise reaching 8 to 16 mm yr^{-1} (SPM, 13). Only collapse of marine-based sectors of the Antarctic ice sheet could cause global mean sea level to rise substantially above these projections, probably not exceeding several tenths of a meter (*medium confidence*) by 2100 (13). Semi-empirical projections of 2100 sea level rise have a wide spread across models, some overlapping with the process-based models and some twice as large; however, there is *low confidence* in these projections (13, 13.5.2, 13.5.3). If global warming exceeds a certain threshold resulting in near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed), global mean sea level would rise about 7 m (13). Future sea level change will vary regionally, but about 70% of the global coastlines are projected to experience a sea level change within 20% of the global mean (13).

The magnitude of extreme high sea level events has increased since 1970 (3). Future sea level extremes will become more frequent beyond 2050, primarily as a result of increasing mean sea level (13). By 2100 the frequency of current sea level extremes will increase by large factors in some regions (13, 13.7.2). Region-specific projections of storminess and associated storm surges have low confidence (13).

Climate patterns. The El Niño-Southern Oscillation (ENSO) system has remained highly variable throughout the past 7000 years with no discernible evidence of orbital modulation (5). The observed variability of the ENSO in the tropical Pacific is now reproduced in most climate models (9). Models project an eastward shift in the ENSO teleconnection patterns of temperature and precipitation variations over the North Pacific and North America (14). ENSO remains the dominant mode of interannual climate variability in the future, and the ENSO precipitation anomalies will intensify due to increased moisture (14). Aggregated over all monsoon systems and over the 21st century, the monsoon will increase in area and intensity while its circulation weakens (14). Monsoon onset dates become earlier or do not change and monsoon retreat dates delay, lengthening the monsoon season (14). Reduced warming and decreased precipitation is projected in the eastern tropical Indian Ocean, with increased warming and precipitation in the western, influencing East Africa and Southeast Asia precipitation (14).

1.3.4. Relevant Findings from IPCC Working Group III Fifth Assessment Report

The WGIII report assesses scientific research related to the mitigation of climate change. Because mitigation lowers the effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts. Both mitigation (WGIII) and adaptation (WGII) involve risk management in the context of many prevailing uncertainties. Uncertainties arise not only in the natural but also in human and social systems, including responses of these to policy interventions. It is possible that extreme climate impacts could play a central role in determining the level of mitigation, adaptation, and other policy responses to climate change (WGIII AR5 Chapter 2).

Over the last two WGIII assessment reports, one of the most important shifts in the scientific literature reflects underlying changes in the structure of the world economy: the underlying determinants of emissions—such as technologies, investment patterns, resource use, lifestyles, and development pathways in general—have not substantially shifted toward a low-GHG pattern despite the adoption of the UNFCCC and the Kyoto Protocol. In 2010, GHG emissions surpassed 50 Gt CO_2-eq (13.6 GtC), higher than in any previous year since 1750. Most of the emission growth between 2000 and 2010 came from fossil-fuel use in the energy and industry sectors, and took place in emerging economies. This emission growth was not met by significant GHG emission cuts in the industrialized country group, which continued to dominate historical long-term contributions to global CO_2 emissions. In 2010, median per capita GHG emissions in high-income countries were roughly 10 times higher than in low-income countries (WGIII AR5 Chapters 1, 5).

One of the central messages of WGIII AR5 is that technological and behavioral options exist that would allow the world's economies to follow pathways to much lower future emissions of GHGs. Since AR4 a substantial scenario literature has emerged on the technological, economic, and institutional conditions needed to achieve different long-term pathways leading to a stabilization of atmospheric GHG concentrations in 2100. A continuation of current trends of technological change in the absence of explicit climate change mitigation policies is not sufficient to bring about stabilization of GHGs. Scenarios that are *more likely than not* to limit temperature increase to 2°C are becoming increasingly challenging, and most of these include a temporary overshoot of this concentration goal requiring net negative CO_2 emissions after 2050 and thus large-scale application of carbon dioxide removal (CDR) technologies (WGIII AR5 Chapter 6). CDR methods are not mature and have biogeochemical and technological limitations to their potential on a global scale and carry side effects and long-term consequences on a global scale (WGI AR5 SPM; WGIII AR5 Chapter 6). The increasing dependence of pathways on CDR options reduces the ability of policymakers to hedge risks freely across the mitigation technology portfolio (WGIII AR5 Chapter 6). The literature highlights the importance of a systemic, cross-sectoral approach to mitigation. Approaches that emphasize only a subset of sectors or a subset of actions may miss synergies between sectors, raise the costs of mitigation, cause unexpected consequences, and prove insufficient to meet long-term mitigation goals (WGIII AR5 Chapters 6 to 11). The costs of mitigation grow over-proportionally with the stringency of the stabilization target. Delays in mitigation and the unavailability of individual mitigation technologies increase the cost of mitigation and negatively affect the probability of meeting ambitious long-term atmospheric stabilization goals (WGIII AR5 Chapter 6).

Mitigation policies involve multiple actors and institutions at the international, regional, national, and sub-national scales—from global treaties to firms and individual households. Since AR4 a body of literature has been emerging to explain how this multiplicity of actors and levels, focused on a multiplicity of interacting goals, affects the design and evolution of mitigation policy (WGIII AR5 Chapters 13, 14, 15). Approaches to international cooperation in climate policies have increased and become more diverse ranging from strong multi-lateralism to harmonized national and regional policies (WGIII AR5 Chapter 13). Linkages among regional, national, and sub-national programs may complement international cooperation. Carbon markets have been the focus of regional policy due, in part, to the greater opportunities for trade as carbon markets expand (WGIII AR5 Chapters 13, 14). A combination of policies that address providing a price signal, removing barriers, and promoting long-term investments could be most effective. If there is no coordination within an integrated perspective then results in one area may be counteracted by results in another area, for instance through leakage and rebound effects (WGIII AR5 Chapter 15).

While mitigation efforts generate costs and trade-offs, they also offer possible synergies because many of the policies that can mitigate GHGs also help address other policy goals, such as managing air pollution, water scarcity, or energy security. Since AR4 a substantial literature has emerged on this topic, underscoring the link of mitigation to a wide range of societal goals, often designated as sustainable development (WGIII AR5 Chapters 3, 4, 15).

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2 Foundations for Decision Making

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Executive Summary

Decision support for impacts, adaptation, and vulnerability is expanding from science-driven linear methods to a wide range of methods drawing from many disciplines (*robust evidence*, *high agreement*). This chapter introduces new material from disciplines including behavioral science, ethics, and cultural and organizational theory, thus providing a broader perspective on climate change decision making. Previous assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. Extensive evidence from the decision sciences shows that while good scientific and technical information is necessary, it is not sufficient, and decisions require context-appropriate decision-support processes and tools (*robust evidence*, *high agreement*). There now exists a sufficiently rich set of available methods, tools, and processes to support effective climate impact, adaptation, and vulnerability (CIAV) decisions in a wide range of contexts (*medium evidence*, *medium agreement*), although they may not always be appropriately combined or readily accessible to decision makers. {2.1.1, 2.1.2, 2.1.3, 2.3}

Risk management provides a useful framework for most climate change decision making. Iterative risk management is most suitable in situations characterized by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socioeconomic and biophysical changes (*robust evidence*, *high agreement*). Complex decision-making contexts will ideally apply a broad definition of risk, address and manage relevant perceived risks, and assess the risks of a broad range of plausible future outcomes and alternative risk management actions (*robust evidence*, *medium agreement*). The resulting challenge is for people and organizations to apply CIAV decision-making processes in ways that address their specific aims. {2.1.2, 2.2.1, 2.3, 2.4.3}

Decision support is situated at the intersection of data provision, expert knowledge, and human decision making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use. Such support is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies (*robust evidence*, *high agreement*). Boundary organizations, including climate services, play an important role in climate change knowledge transfer and communication, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*). {2.1.3, 2.2.1, 2.2, 2.3, 2.4.1, 2.4.2, 2.4.3}

Scenarios are a key tool for addressing uncertainty (*robust evidence*, *high agreement*). They can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration). Historically, most scenarios used for CIAV assessments have been of the former type, though the latter are becoming more prevalent (*medium evidence*, *high agreement*). The new RCP scenario process can address both problem and solution framing in ways that previous IPCC scenarios have not been able to (*limited evidence*, *medium agreement*). {2.2.1.3, 2.3.2}

CIAV decision making involves ethical judgments expressed at a range of institutional scales; the resulting ethical judgements are a key part of risk governance (*robust evidence*, *medium agreement*). Recognition of local and indigenous knowledge and diverse stakeholder interests, values, and expectations is fundamental to building trust within decision-making processes (*robust evidence*, *high agreement*). {2.2.1.1, 2.2.1.2, 2.2.1.3, 2.2.1.4, 2.4, 2.4.1}

Climate services aim to make knowledge about climate accessible to a wide range of decision makers. In doing so they have to consider information supply, competing sources of knowledge, and user demand. Knowledge transfer is a negotiated process that takes a variety of cultural values, orientations, and alternative forms of knowledge into account (*medium evidence*, *high agreement*). {2.4.1, 2.4.2}

Climate change response can be linked with sustainable development through actions that enhance resilience, the capacity to change in order to maintain the same identity while also maintaining the capacity to adapt, learn, and transform. Mainstreamed adaptation, disaster risk management, and new types of governance and institutional arrangements are being studied for their potential to support the goal of enhanced resilience (*medium evidence*, *high agreement*). {2.5.2}

Transformational adaptation may be required if incremental adaptation proves insufficient (*medium evidence*, *high agreement*). This process may require changes in existing social structures, institutions, and values, which can be facilitated by iterative risk management and triple-loop learning that considers a situation and its drivers, along with the underlying frames and values that provide the situation context. {2.1.2, 2.5.3}

2.1. Introduction and Key Concepts

This chapter addresses the foundations of decision making with respect to climate impact, adaptation, and vulnerability (CIAV). The Fourth Assessment Report (AR4) summarized methods for assessing CIAV (Carter et al., 2007), which we build on by surveying the broader literature relevant for decision making.

Decision making under climate change has largely been modeled on the scientific understanding of the cause-and-effect process whereby increasing greenhouse gas emissions cause climate change, resulting in changing impacts and risks, potentially increasing vulnerability to those risks. The resulting decision-making guidance on impacts and adaptation follows a rational-linear process that identifies potential risks and then evaluates management responses (e.g., Carter et al., 1994; Feenstra et al., 1998; Parry and Carter, 1998; Fisher et al., 2007). This process has been challenged on the grounds that it does not adequately address the diverse contexts within which climate decisions are being made, often neglects existing decision-making processes, and overlooks many cultural and behavioral aspects of decision making (Smit and Wandel, 2006; Sarewitz and Pielke, 2007; Dovers, 2009; Beck, 2010). While more recent guidance on CIAV decision making typically accounts for sectoral, regional, and socioeconomic characteristics (Section 21.3), the broader decision-making literature is still not fully reflected in current methods. This is despite an increasing emphasis on the roles of societal impacts and responses to climate change in decision-making methodologies (*high confidence*) (Sections 1.1, 1.2, 21.2.1).

The main considerations that inform the decision-making contexts addressed here are knowledge generation and exchange, who makes and implements decisions, and the issues being addressed and how these can be addressed. These decisions occur within a broader social and cultural environment. Knowledge generation and exchange includes knowledge generation, development, brokering, exchange, and application to practice. Decision makers include policymakers, managers, planners, and practitioners, and range from individuals to organizations and institutions (Table 21-1). Relevant issues include all areas affected directly and indirectly by climate impacts or by responses to those impacts, covering diverse aspects of society and the environment. These issues include consideration of values, purpose, goals, available resources, the time over which actions are expected to remain effective, and the extent to which the objectives being pursued are regarded as appropriate. The purpose of the decision in question, for example, assessment, strategic planning, or implementation, will also define the framework and tools needed to enable the process. This chapter neither provides any standard template or instructions for decision making, nor does it endorse particular decisions over others.

The remainder of this chapter is organized as follows. Section 2.1.2 addresses risk management, which provides an overall framework suitable for CIAV decision making; Section 2.1.3 introduces decision support; Section 2.2 discusses contexts for decision making; Section 2.3 discusses methods, tools, and processes; Section 2.4 discusses support for and application of decision making; and Section 2.5 describes some of the broader contexts influencing CIAV decision making.

2.1.1. Decision-Making Approaches in this Report

The overarching theme of the chapter and the AR5 report is managing current and future climate risks (Sections 1.2.4, 16.2, 19.1), principally through adaptation (Chapters 14 to 17), but also through resilience and sustainable development informed by an understanding of both impacts and vulnerability (Section 19.2). The International Standard ISO:31000 defines risk as *the effect of uncertainty on objectives* (ISO, 2009) and the Working Group II AR5 Glossary defines risk as *The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain* (Rosa, 2003). However, the Glossary also refers to a more operational definition for assessing climate-related hazards: *risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.* Risk can also refer to an uncertain opportunity or benefit (see Section 2.2.1.3). This chapter takes a broader perspective than the latter by including risks associated with taking action (e.g., will this adaptation strategy be successful?) and the broader socially constructed risks that surround "climate change" (e.g., fatalism, hope, opportunity, and despair).

Because all decisions on CIAV are affected by uncertainty and focus on valued objectives, all can be considered as decisions involving risk (e.g., Giddens, 2009) (*high confidence*). AR4 endorsed iterative risk management as a suitable decision support framework for CIAV assessment because it offers formalized methods for addressing uncertainty, involving stakeholder participation, identifying potential policy responses, and evaluating those responses (Carter et al., 2007; IPCC, 2007b; Yohe et al., 2007). The literature shows significant advances on all these topics since AR4 (Section 1.1.4), greatly expanding methodologies for assessing impacts, adaptation, and vulnerability in a risk context (Agrawala and Fankhauser, 2008; Hinkel, 2011; Jones and Preston, 2011; Preston et al., 2011).

Many different risk methodologies, such as financial, natural disaster, infrastructure, environmental health, and human health, are relevant for CIAV decision making (*very high confidence*). Each methodology utilizes a variety of different tools and methods. For example, the standard CIAV methodology follows a top-down cause and effect pathway as outlined previously. Others follow a bottom-up pathway, starting with a set of decision-making goals that may be unrelated to climate and consider how climate may affect those goals (see also Sections 15.2.1, 15.3.1). Some methodologies such as vulnerability, resilience, and livelihood assessments are often considered as being different from traditional risk assessment, but may be seen as dealing with particular stages within a longer term iterative risk management process. For example, developing resilience can be seen as managing a range of potential risks that are largely unpredictable; and sustainable development aims to develop a social-ecological system robust to climate risks.

A major aim of decision making is to make good or better decisions. Good and better decisions with respect to climate adaptation are frequently mentioned in the literature but no universal criterion exists for a good decision, including a good climate-related decision (Moser and Ekstrom, 2010). This is reflected in the numerous framings linked to adaptation decision making, each having its advantages and disadvantages

Frequently Asked Questions

FAQ 2.1 | What constitutes a good (climate) decision?

No universal criterion exists for a good decision, including a good climate-related decision. Seemingly reasonable decisions can turn out badly, and seemingly unreasonable decisions can turn out well. However, findings from decision theory, risk governance, ethical reasoning, and related fields offer general principles that can help improve the quality of decisions made.

Good decisions tend to emerge from processes in which people are explicit about their goals; consider a range of alternative options for pursuing their goals; use the best available science to understand the potential consequences of their actions; carefully consider the trade-offs; contemplate the decision from a wide range of views and vantages, including those who are not represented but may be affected; and follow agreed-upon rules and norms that enhance the legitimacy of the process for all those concerned. A good decision will be implementable within constraints such as current systems and processes, resources, knowledge, and institutional frameworks. It will have a given lifetime over which it is expected to be effective, and a process to track its effectiveness. It will have defined and measurable criteria for success, in that monitoring and review is able to judge whether measures of success are being met, or whether those measures, or the decision itself, need to be revisited.

A good climate decision requires information on climate, its impacts, potential risks, and vulnerability to be integrated into an existing or proposed decision-making context. This may require a dialog between users and specialists to jointly ascertain how a specific task can best be undertaken within a given context with the current state of scientific knowledge. This dialog may be facilitated by individuals, often known as knowledge brokers or extension agents, and boundary organizations, who bridge the gap between research and practice. Climate services are boundary organizations that provide and facilitate knowledge about climate, climate change, and climate impacts for planning, decision making, and general societal understanding of the climate system.

(Preston et al., 2013; see also Section 15.2.1). Extensive evidence from the decision sciences shows that good scientific and technical information alone is rarely sufficient to result in better decisions (Bell and Lederman, 2003; Jasanoff, 2010; Pidgeon and Fischhoff, 2011) (*high confidence*). Aspects of decision making that distinguish climate change from most other contexts are the long time scales involved, the pervasive impacts and resulting risks, and the “deep” uncertainties attached to many of those risks (Kandlikar et al., 2005; Ogden and Innes, 2009; Lempert and McKay, 2011). These uncertainties include not only future climate but also socioeconomic change and potential changes in norms and values within and across generations.

2.1.2. Iterative Risk Management

Iterative risk management involves an ongoing process of assessment, action, reassessment, and response (Kambhu et al., 2007; IRGC, 2010) that will continue—in the case of many climate-related decisions—for decades if not longer (National Research Council, 2011). This development is consistent with an increasing focus on risk governance (Power, 2007; Renn, 2008), the integration of climate risks with other areas of risk management (Hellmuth et al., 2011; Measham et al., 2011), and a wide range of approaches for structured decision making involving process uncertainty (Ohlson et al., 2005; Wilson and McDaniels, 2007; Ogden and Innes, 2009; Martin et al., 2011).

Two levels of interaction can be recognized within the iterative risk management process: one internal and one external (Figure 2-1). External factors are present through the entire process and shape the process outcomes. The internal aspects describe the adaptation process itself. The first major internal iteration (in yellow) reflects the interplay with the analysis phase by addressing the interactions between evolving risks and their feedbacks (not shown) and during the development and choice of options. This process may also require a revision of criteria and objectives. This phase ends with decisions on the favored options being made. A further internal iteration covers the implementation of actions and their monitoring and review (in orange). Throughout all stages the process is reflexive, in order to enable changes in knowledge, risks, or circumstances to be identified and responded to. At the end of the implementation stage, all stages are evaluated and the process starts again with the scoping phase. Iterations can be successive, on a set timetable, triggered by specific criteria or informally by new information informing risk or a change in the policy environment. An important aspect of this process is to recognize emergent risks and respond to them (Sections 19.2.3, 19.2.4, 19.2.5, 19.3).

Complexity is an important attribute for framing and implementing decision-making processes (*very high confidence*). Simple, well-bounded contexts involving cause and effect can be addressed by straightforward linear methods. Complicated contexts require greater attention to process but can generally be unravelled, providing an ultimate solution (Figure 2-2). However, when complex environments interact with conflicting values they become associated with wicked problems. Wicked problems are not well bounded, are framed differently by various groups and individuals, harbor large scientific to existential uncertainties and have unclear solutions and pathways to those solutions (Rittel and Webber,

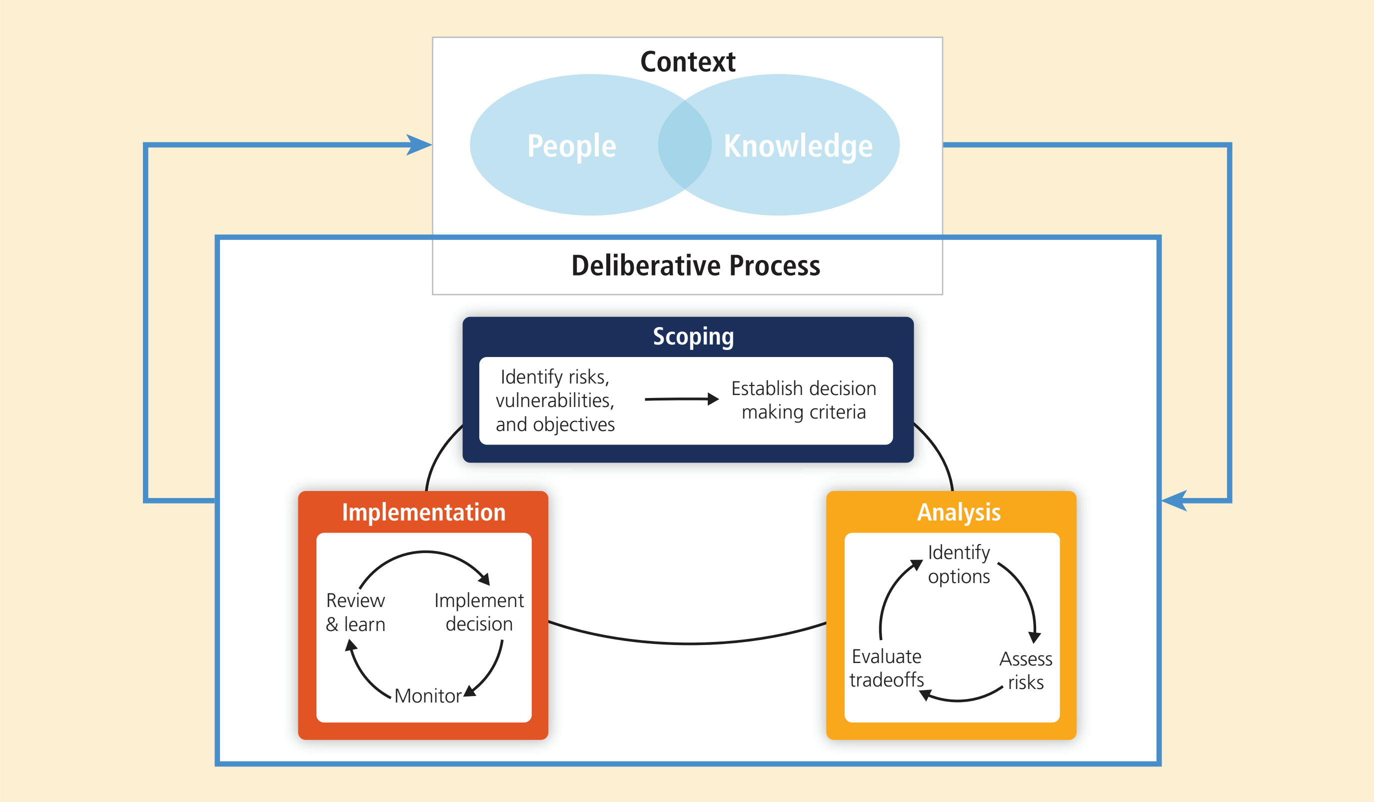


Figure 2-1 | Iterative risk management framework depicting the assessment process, and indicating multiple feedbacks within the system and extending to the overall context (adapted from Willows and Connell, 2003).

1973; Australian Public Service Commission, 2007). Such "deep uncertainty" cannot easily be quantified (Dupuy and Grinbaum, 2005; Kandlikar et al., 2005). Another important attribute of complex systems is *reflexivity*, where cause and effect feed back into each other (see Glossary). For example, actions taken to manage a risk will affect the outcomes, requiring iterative processes of decision making (*very high confidence*). Under climate change, calculated risks will also change with time as new knowledge becomes available (Ranger et al., 2010).

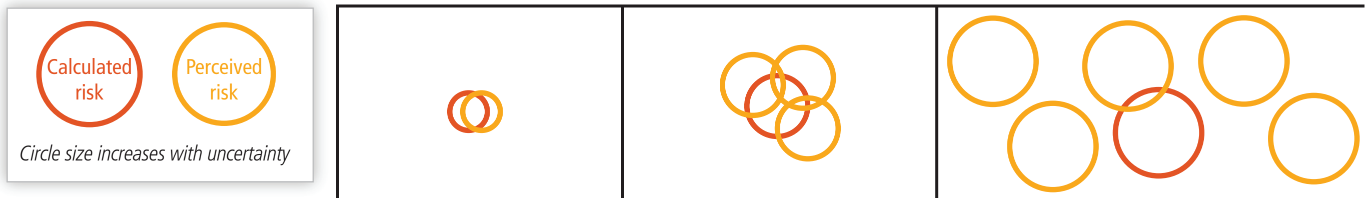
In complex situations, sociocultural and cognitive-behavioral contexts become central to decision making. This requires combining the scientific understanding of risk with how risks are framed and perceived by individuals, organizations, and institutions (Hansson, 2010). For that reason, formal risk assessment is moving from a largely technocratic exercise carried out by experts to a more participatory process of decision support (Fiorino, 1990; Pereira and Quintana, 2002; Renn, 2008), although this process is proceeding slowly (Christoplos et al., 2001; Pereira and Quintana, 2002; Bradbury, 2006; Mercer et al., 2008).

Different traditional and modern epistemologies, or "ways of knowing" exist for risk (Hansson, 2004; Althaus, 2005; Hansson, 2010), vulnerability (Weichselgartner, 2001; O'Brien et al., 2007), and adaptation assessments (Adger et al., 2009), affecting the way they are framed by various disciplines and are also understood by the public (Garvin, 2001; Adger, 2006; Burch and Robinson, 2007). These differences have been identified as a source of widespread misunderstanding and disagreement. They are also used to warn against a uniform epistemic approach (Hulme, 2009; Beck, 2010), a critique that has been leveled against previous IPCC assessments (e.g., Hulme and Mahony, 2010).

The following three types of risk have been identified as important epistemological constructs (Thompson, 1986; Althaus, 2005; Jones, 2012):

1. Idealized risk: the conceptual framing of the problem at hand. For example, dangerous anthropogenic interference with the climate system is how climate change risk is idealized within the UNFCCC.
2. Calculated risk: the product of a model based on a mixture of historical (observed) and theoretical information. Frequentist or recurrent risks often utilize historical information whereas single-event risks may be unprecedented, requiring a more theoretical approach.
3. Perceived risk: the subjective judgment people make about an idealized risk (see also Section 19.6.1.4).

These different types show risk to be partly an objective threat of harm and partly a product of social and cultural experience (Kasperson et al., 1988; Kasperson, 1992; Rosa, 2008). The aim of calculating risk is to be as objective as possible, but the subjective nature of idealized and perceived risk reflects the division between positivist (imposed norms) and constructivist (derived norms) approaches to risk from the natural and social sciences respectively (Demeritt, 2001; Hansson, 2010). Idealized risk is important for framing and conceptualizing risk and will often have formal and informal status in the assessment process, contributing to both calculated and perceived risk. These types of risk combine at the societal scale as socially constructed risk, described and



Characteristics of decision making	Simple risk	Complicated risk	Complex risk
Methodology	Linear, cause and effect	Top down and/or bottom up, iterative	Iterative and/or adaptive, ongoing and systemic
Approach	Analytic and technical	Collaborative process with technical input	Process driven. Frame and model multiple drivers and valued outcomes
Stakeholder strategy	Communication	Collaboration	Deliberation, creating shared understanding and ownership
Mental models	Common model	Negotiated and shared	Contested initially and negotiated over project
Values and outcomes	Widely accepted	Negotiated over project by user perspectives and calculated risk	Contested initially and negotiated over project
Monitoring	Straightforward	With review and trigger points	As real-time as possible, adaptive with management feedback and trigger points

Figure 2-2 | Hierarchy of simple, complicated, and complex risks, showing how perceived risks multiply and become less connected with calculated risk with increasing complexity. Also shown are major characteristics of assessment methods for each level of complexity.

assessed in a wide range of research literature such as psychology, anthropology, geography, ethics, sociology, and political science (see Sections 2.2.1.2, 19.6.1.4).

Acceptance of the science behind controversial risks is strongly influenced by social and cultural values and beliefs (Leiserowitz, 2006; Kahan et al., 2007; Brewer and Pease, 2008). Risk perceptions can be amplified socially where events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that heighten or attenuate individual and social perceptions of risk and shape risk behavior (Kasperson et al., 1988; Renn et al., 1992; Pidgeon et al., 2003; Rosa, 2003; Renn, 2011). The media have an important role in propagating both calculated and perceived risk (Llasat et al., 2009), sometimes to detrimental effect (Boykoff and Boykoff, 2007; Oreskes and Conway, 2010; Woods et al., 2012).

Understanding how these perceptions resonate at an individual and collective level can help overcome constraints to action (Renn, 2011). Science is most suited to calculating risk in areas where it has predictive skill and will provide better estimates than may be obtained through more informal methods (Beck, 2000), but an assessment of what is at risk generally needs to be accepted by stakeholders (Eiser et al., 2012). Therefore, the science always sits within a broader social setting (Jasanoff, 1996; Demeritt, 2001; Wynne, 2002; Demeritt, 2006), often requiring a systems approach where science and policy are investigated in tandem, rather than separately (Pahl-Wostl, 2007; Ison, 2010) (*very high confidence*). These different types of risk give rise to complex interactions between formal and informal knowledge that cannot be bridged by better science or better predictions but require socially and culturally mediated processes of engagement (*high confidence*).

2.1.3. Decision Support

The concept of *decision support* provides a useful framework for understanding how risk-based concepts and information can help enhance decision making (McNie, 2007; National Research Council Panel on Design Issues for the NOAA Sectoral Applications Research Program et al., 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011) The concept also helps situate methods, tools, and processes intended to improve decision making within appropriate institutional and cultural contexts.

Decision support is defined as "a set of processes intended to create the conditions for the production of decision-relevant information and for its appropriate use" (National Research Council, 2009a, p. 33). Information is decision-relevant if it yields deeper understanding of, or is incorporated into making a choice that improves outcomes for decision makers and stakeholder or precipitates action to manage known risks. Effective decision support provides users with information they find useful because they consider it credible, legitimate, actionable, and salient (e.g., Jones et al., 1999; Cash et al., 2003; Mitchell, 2006; Reid et al., 2007). Such criteria can be used to evaluate decision support and such evaluations lead to common principles of effective decision support, which have been summarized in National Research Council (2009b) as:

- Begins with user's needs, not scientific research priorities. Users may not always know their needs in advance, so user needs are often developed collaboratively and iteratively among users and researchers.
- Emphasizes processes over products. Though the information products are important, they are likely to be ineffective if they are not developed to support well-considered processes.

- Incorporates systems that link users and producers of information. These systems generally respect the differing cultures of decision makers and scientists, but provide processes and institutions that effectively link individuals from these differing communities.
- Builds connections across disciplines and organizations, in order to provide for the multidisciplinary character of the needed information and the differing communities and organizations in which this information resides.
- Seeks institutional stability, either through stable institutions and/or networks, which facilitates building the trust and familiarity needed for effective links and connections among information users and producers in many different organizations and communities.
- Incorporates learning, so that all parties recognize the need for and contribute to the implementation of decision support activities structured for flexibility, adaptability, and learning from experience.

These principles can lead to different decision support processes depending on the stage and context of the decision in question. For instance, decision support for a large water management agency operating an integrated system serving millions of people will have different needs than a small town seeking to manage its groundwater supplies. A community in the early stages of developing a response to climate change may be more focused on raising awareness of the issue among its constituents, while a community with a well-developed understanding of its risks may be more focused on assessing trade-offs and allocating resources.

2.2. Contexts for Decision Making

This section surveys aspects of decision making that relate to context setting. Social context addresses cultural values, psychology, language, and ethics (Section 2.2.1) and institutional context covers institutions and governance (Section 2.2.2).

2.2.1. Social Context

Decision support for CIAV must recognize that diverse values, language uses, ethics, and human psychological dimensions play a crucial role in the way that people use and process information and take decisions (Kahan and Braman, 2006; Leiserowitz, 2006). As illustrated in Figure 2-1, the context defines and frames the space in which decision-making processes operate.

2.2.1.1. Cultural Values and Determinants

Cultural differences allocate values and guide socially mediated change. Five value dimensions that show significant cross-national variations are: power distance, individualism/collectivism, uncertainty avoidance, long-/short-term orientation, and masculinity/femininity (Hofstede, 1980, 2001; Hofstede et al., 2010). Power distance and individualism/collectivism both show a link to climate via latitude; the former relates to willingness to conform to top-down directives, whereas the latter relates to the potential efficacy of market-/community-based strategies. Uncertainty avoidance and long-term orientation show considerable variation between countries (Hofstede et al., 2010), potentially producing significant differences in risk perception and agency.

Environmental values have also been linked to cultural orientation. Schultz et al. (2004) identified the association between self and nature in people as being implicit—informing actions without specific awareness. A strong association was linked to a more connected self and a weaker association with a more egoistic self. Explicit environmental values can substantially influence climate change-related decision-making processes (Nilsson et al., 2004; Milfont and Gouveia, 2006; Soyez et al., 2009) and public behavior toward policies (Stern and Dietz, 1994; Xiao and Dunlap, 2007). Schaffrin (2011) concludes that geographical aspects, vulnerability, and potential policy benefits associated with a given issue can influence individual perceptions and willingness to act (De Groot and Steg, 2007, 2008; Shwom et al., 2008; Milfont et al., 2010). Cultural values can interrelate with specific physical situations of climate change (Corraliza and Berenguer, 2000), or seasonal and meteorological factors influencing people's implicit connections with nature (Duffy and Verges, 2010). Religious and sacred values are also important (Goloubinoff, 1997; Katz et al., 2002; Lammel et al., 2008), informing the perception of climate change and risk, as well as the actions to adapt (Crate and Nuttal, 2009; see also Section 16.3.1.3). The role of protected values (values that people will not trade off, or negotiate) can also be culturally and spiritually significant (Baron and Spranca, 1997; Baron et al., 2009; Hagerman et al., 2010). Adger et al. (2013) emphasize the importance of cultural values in assessing risks and adaptation options, suggesting they are at least as important as economic values in many cases, if not more so. These aspects are important for framing and conceptualizing CIAV decision making. Cultural and social barriers are described in Section 16.3.2.7.

Two distinct ways of thinking—holistic and analytical thinking—reflect the relationship between humans and nature and are cross-culturally and even intra-culturally diverse (Gagnon Thompson and Barton, 1994; Huber and Pedersen, 1997; Atran et al., 2005; Ignatow, 2006; Descola, 2010; Ingold, 2011). Holistic thinking is primarily gained through experience and is dialectical, accepting contradictions and integrating multiple perspectives. Characteristic of collectivist societies, the holistic conceptual model considers that social obligations are reciprocal and individuals take an active part in the community for the benefit of all (Peng and Nisbett, 1999; Nisbett et al., 2001; Lammel and Kozakai, 2005; Nisbett and Miyamoto, 2005). Analytical thinking isolates the object from its broader context, understanding its characteristics through categorization, and predicting events based on intrinsic rules. In the analytic conceptual model, individual interests take precedence over the collective; the self is independent and communication comes from separate fields. These differences influence the understanding of complex systemic phenomena such as climate change (Lammel et al., 2011, 2012, 2013) and decision-making practices (Badke-Schaub and Strohschneider, 1998; Strohschneider and Güss, 1999; Güss et al., 2010).

The above models vary greatly across the cultural landscape, but neither model alone is sufficient for decision making in complex situations (*high confidence*). At a very basic level, egalitarian societies may respond more to community based adaptation in contrast to more individualistic societies that respond to market-based forces (*medium confidence*). In small-scale societies, knowledge about climate risks are often integrated

2

into a holistic view of community and environment (e.g., Katz et al., 2002; Strauss and Orlove, 2003; Lammel et al., 2008). Many studies highlight the importance of integrating local, traditional knowledge with scientific knowledge when assessing CIAV (Magistro and Roncoli, 2001; Krupnik and Jolly, 2002; Vedwan, 2006; Nyong et al., 2007; Dube and Sekhwela, 2008; Crate and Nuttal, 2009; Mercer et al., 2009; Roncoli et al., 2009; Green and Raygorodetsky, 2010; Orlove et al., 2010; Crate, 2011; Nakashima et al., 2012; see also Sections 12.3, 12.3.1, 12.3.2, 12.3.3, 12.3.4, 14.4.5, 14.4.7, 15.3.2.7, 25.8.2, 28.2.6.1, 28.4.1). For example, a case study in Labrador (Canada) demonstrated the need to account for local material and symbolic values because they shape the relationship to the land, underlie the way of life, influence the intangible effects of climate change, and can lead to diverging views on adaptations (Wolf et al., 2012). In Kiribati, the integration of local cultural values attached to resources/assets is fundamental to adaptation planning and water management; otherwise technology will not be properly utilized (Kuruppu, 2009).

2.2.1.2. Psychology

Psychology plays a significant role in climate change decision making (Gifford, 2008; Swim et al., 2010; Anderson, 2011). Important psychological factors for decision making include perception, representation, knowledge acquisition, memory, behavior, emotions, and understanding of risk (Böhm and Pfister, 2000; Leiserowitz, 2006; Lorenzoni et al., 2006; Oskamp and Schultz, 2006; Sterman and Sweeney, 2007; Gifford, 2008; Kazdin, 2009; Sundblad et al., 2009; Reser et al., 2011; Swim et al., 2011).

Psychological research contributes to understanding on both risk perception and the process of adaptation. Several theories, such as multi-attribute utility theory (Keeney, 1992), prospect theory (Kahneman and Tversky, 1979; Hardman, 2009), and cumulative prospect theory relate to decision making under uncertainty (Tversky and Kahneman, 1992), especially to risk perception and agency. Adaptation in complex situations pits an unsure gain against an unsure loss, so creates an asymmetry in preference that magnifies with time as gains/losses are expected to accrue in future. Decisions focusing on values and uncertainty are therefore subject to framing effects. Recent cognitive approaches include the one-reason decision process that uses limited data in a limited time period (Gigerenzer and Goldstein, 1996) or decision by sampling theory that samples real-world data to account for the cognitive biases observed in behavioral economics (Stewart et al., 2006; Stewart and Simpson, 2008). Risk perception is further discussed in Section 19.6.1.4.

Responses to new information can modify previous decisions, even producing contradictory results (Grothmann and Patt, 2005; Marx et al., 2007). Although knowledge about climate change is necessary (Milfont, 2012), understanding such knowledge can be difficult (Rajeev Gowda et al., 1997; Boyes et al., 1999; Andersson and Wallin, 2000). Cognitive obstacles in processing climate change information include psychological distances with four theorized dimensions: temporal, geographical, social distance, and uncertainty (Spence et al., 2012; see also Section 25.4.3). Emotional factors also play an important role in climate change perception, attitudes, decision making, and actions (Meijnders et al., 2002; Leiserowitz, 2006; Klöckner and Blöbaum, 2010; Fischer and Glenk 2011; Roeser, 2012) and even shape organizational decision making (Wright and Nyberg, 2012). Other studies on attitudes and behaviors relevant to climate change decision making, include place attachment (Scannell and Gifford, 2013; see also Section 25.4.3), political affiliation (Davidson and Haan, 2011), and perceived costs and benefits (Tobler et al., 2012). Time is a critical component of action-based decision making (Steel and König, 2006). As the benefits of many climate change actions span multiple temporal scales, this can create a barrier to effective motivation for decisions through a perceived lack of value associated with long-term outcomes.

Protection Motivation Theory (Rogers, 1975; Maddux and Rogers, 1983), which proposes that a higher personal perceived risk will lead to a higher motivation to adapt, can be applied to climate change-related problems (e.g., Grothmann and Reusswig, 2006; Cismaru et al., 2011). The person-relative-to-event approach predicts human coping strategies as a function of the magnitude of environmental threat (Mulilis and Duval, 1995; Duval and Mulilis, 1999; Grothmann et al., 2013). People's responses to environmental hazards and disasters are represented in the multistage Protective Action Decision Model (Lindell and Perry, 2012). This model helps decision makers to respond to long-term threat and apply it in long-term risk management. Grothmann and Patt (2005) developed and tested a socio-cognitive model of proactive private adaptation to climate change showing that perceptions of adaptive capacities were important as well as perceptions of risk. If a perceived high risk is combined with a perceived low adaptive capacity (see Section 2.4.2.2; Glossary), the response is fatalism, denial, and wishful thinking.

Best-practice methods for incorporating and communicating information about risk and uncertainties into decisions about climate change (Climate Change Science Program, 2009; Pidgeon and Fischhoff, 2011) suggests that effective communication of uncertainty requires products and processes that (1) closes psychological distance, explaining why this information is important to the recipient; (2) distinguishes between and explains different types of uncertainty; (3) establishes self-agency, explaining what the recipient can do with the information and ways to make decisions under uncertainty (e.g., precautionary principle, iterative risk-management); (4) recognizes that each person's view of risks and opportunities depends on their values; (5) recognizes that emotion is a critical part of judgment; and (6) provides mental models that help recipients to understand the connection between cause and effect. Information providers also need to test their messages, as they may not be communicating what they think they are.

2.2.1.3. Language and Meaning

Aspects of decision making concerned with language and meaning include framing, communication, learning, knowledge exchange, dialog, and discussion. Most IPCC-related literature on language and communication deals with definitions, predictability, and incomplete knowledge, with less emphasis given to other aspects of decision support such as learning, ambiguity, contestedness, and complexity. Three important areas assessed here are definitions, risk language and communication, and narratives.

Decision-making processes need to accommodate both specialist and non-specialist meanings of the concepts they apply. Various disciplines often have different definitions for the same terms or use different terms for the same action or object, which is a major barrier for communication and decision making (Adger, 2003; see also Chapter 21). For example, adaptation is defined differently with respect to biological evolution, climate change, and social adaptation. Budescu et al. (2012) found that people prefer imprecise wording but precise numbers when appropriate. Personal lexicons vary widely, leading to differing interpretations of uncertainty terms (Morgan et al., 1990); in the IPCC's case leading to uncertainty ranges often being interpreted differently than intended (Patt and Schrag, 2003; Patt and Dessai, 2005; Budescu et al., 2012). Addressing both technical and everyday meanings of key terms can help bridge the analytic and emotive aspects of cognition. For example, words like danger, disaster, uncertainty, and catastrophe have technical and emotive aspects (Britton, 1986; Carvalho and Burgess, 2005). Terms where this issue is especially pertinent include adaptation, vulnerability, risk, dangerous, catastrophe, resilience, and disaster. Other words have definitional issues because they contain different epistemological frames; sustainability and risk are key examples (Harding, 2006; Hamilton et al., 2007). Many authors advocate that narrow definitions focused solely on climate need to be expanded to suit the context in which they are being used (Huq and Reid, 2004; O'Brien et al., 2007; Schipper, 2007). This is a key role for risk communication, ensuring that different types of knowledge are integrated within decision context and outlining the different values—implicit and explicit—involved in the decision process (e.g., Morgan, 2002; Lundgren and McMakin, 2013).

The language of risk has a crucial role in framing and belief. Section 2.1.2 described over-arching and climate-specific definitions but risk enters into almost every aspect of social discourse, so is relevant to how risk is framed and communicated (e.g., Hansson, 2004). Meanings of risk range from its ordinary use in everyday language to power and political discourse, health, emergency, disaster, and seeking benefits, ranging from specific local meanings to broad-ranging concepts such as the risk society (Beck and Ritter, 1992; Beck, 2000; Giddens, 2000). Complex framings in the word risk (Fillmore and Atkins, 1992; Hamilton et al., 2007) feature in general English as both a noun and a verb, reflecting harm and chance with negative and positive senses (Fillmore and Atkins, 1992). Problem analysis applies risk as a noun (at-risk), whereas risk management applies risk as a verb (to-risk) (Jones, 2011). For simple risks, this transition is straightforward because of agreement around values and agency (Figure 2-2). In complex situations, risk as a problem and as an opportunity can compete with each other, and if socially amplified can lead to action paralysis (Renn, 2011). For example, unfamiliar adaptation options that seem to be risky themselves will force a comparison between the risk of maladaptation and future climate risks, echoing the risk trap where problems and solutions come into conflict (Beck, 2000). Fear-based dialogs in certain circumstances can cause disengagement (O'Neill and Nicholson-Cole, 2009), by emphasizing risk aversion. Young (2013) proposes framing adaptation as a solution to overcome the limitations of framing through the problem, and links it to innovation, which provides established pathways for the implementation of actions, proposing a problem-solution framework linking decision making to action. Framing decisions and modeling actions on positive risk-seeking behavior can help people to address uncertainty as opportunity (e.g., Keeney, 1992).

Narratives are accounts of events with temporal or causal coherence that may be goal directed (László and Ehmann, 2012) and play a key role in communication, learning, and understanding. They operate at the personal to societal scales, are key determinants of framing, and have a strong role in creating social legitimacy. Narratives can also be non-verbal: visualization, kinetic learning by doing, and other sensory applications can be used to communicate science and art and to enable learning through play (Perlovsky, 2009; Radford, 2009). Narratives of climate change have evolved over time and invariably represent uncertainty and risk (Hamblyn, 2009) being characterized as tools for analysis, communication, and engagement (Cohen, 2011; Jones et al., 2013; Westerhoff and Robinson, 2013) by:

- Providing a social and environmental context to modelled futures (Arnell et al., 2004; Kriegler et al., 2012; O'Neill et al., 2014), by describing aspects of change that drive or shape those futures as part of scenario construction (Cork et al., 2012).
- Communicating knowledge and ideas to increase understanding and increase agency framing it in ways so that actions can be implemented (Juhola et al., 2011) or provide a broader socio-ecological context to specific knowledge (Burley et al., 2012). These narratives bridge the route between scientific knowledge and local understandings of adaptation, often by working with multiple actors in order to creatively explore and develop collaborative potential solutions (Turner and Clifton, 2009; Paton and Fairbairn-Dunlop, 2010; Tschakert and Dietrich, 2010).
- Exploring responses at an individual/institutional level to an aspect of adaptation, and communicating that experience with others (Bravo, 2009; Cohen, 2011). For example, a community that believes itself to be resilient and self-reliant is more likely to respond proactively, contrasted to a community that believes itself to be vulnerable (Farbotko and Lazrus, 2012). Bravo (2009) maintains that narratives of catastrophic risk and vulnerability demotivate indigenous peoples whereas narratives combining scientific knowledge and active citizenship promote resilience (Section2.5.2).

2.2.1.4. Ethics

Climate ethics can be used to formalize objectives, values (Section 2.2.1.1), rights, and needs into decisions, decision-making processes, and actions (see also Section 16.7). Principal ethical concerns include intergenerational equity; distributional issues; the role of uncertainty in allocating fairness or equity; economic and policy decisions; international justice and law; voluntary and involuntary levels of risk; cross-cultural relations; and human relationships with nature, technology, and the sociocultural world. Climate change ethics have been developing over the last 20 years (Jamieson, 1992, 1996; Gardiner, 2004; Gardiner et al., 2010), resulting in a substantial literature (Garvey, 2008; Harris, 2010; O'Brien et al., 2010; Arnold, 2011; Brown, 2012; Thompson and Bendik-Keymer, 2012). Equity, inequity, and responsibility are fundamental concepts in the UNFCCC (UN, 1992) and therefore are important considerations in policy development for CIAV. Climate ethics examine effective responsible and "moral" decision making and action, not only by governments but also by individuals (Garvey, 2008).

An important discourse on equity is that industrialized countries have, through their historical emissions, created a natural debt (Green and

Smith, 2002). Developing nations experience this debt through higher impacts and greater vulnerability combined with limited adaptive capacity. Regional inequity is also of concern (Green and Smith, 2002), particularly indigenous or marginalized populations exposed to current climate extremes, who may become more vulnerable under a changing climate (Tsosie, 2007; see also Section 12.3.3). With respect to adaptation assessment, cost-benefit or cost-effectiveness methods combined with transfer of funds will not satisfy equity considerations (Broome, 2008; see also Section 17.3.1.4) and modifications such as equity-weighting (Kuik et al., 2008) and cost-benefit under uncertainty (Section 17.3.2.1), have not been widely used. Adaptation measures need to be evaluated by considering their equity implications (Section 17.3.1.4) especially under uncertainty (Hansson, 2004).

Intergenerational issues are frequently treated as an economic problem, with efforts to address them through an ethical framework proving to be controversial (Nordhaus, 2007; Stern and Treasury of Great Britain, 2007; Stern, 2008). However, future harm may make the lives of future generations difficult or impossible, dilemmas that involve ethical choices (Broome, 2008), therefore discount rates matter (Section 17.4.4.4). Some authors question whether the rights and interests of future people should even be subject to a positive discount rate (Caney, 2009). Future generations can neither defend themselves within current economic frameworks (Gardiner, 2011) nor can these frameworks properly account for the dangers, interdependency, and uncertainty under climate change (Nelson, 2011), even though people's values may change over time (Section 16.7). The limits to adaptation raise questions of irreversible loss and the loss of unique cultural values that cannot necessarily be easily transferred (Section 16.7), contributing to key vulnerabilities and informing ethical issues facing mitigation (see Section 19.7.1).

Environmental ethics considers the decisions humans may make concerning a range of biotic impacts (Schalow, 2000; Minteer and Collins, 2010; Nanda, 2012; Thompson and Bendik-Keymer, 2012). Intervention in natural systems through "assisted colonization" or "managed relocation" raises important ethical and policy questions (Minteer and Collins, 2010; Section 4.4.2.4) that include the risk of unintended consequences (Section 4.4.4). Various claims are made for a more pragmatic ethics of ecological decision making (Minteer and Collins, 2010), consideration of moral duties toward species (Sandler, 2009), and ethically explicit and defendable decision making (Minteer and Collins, 2005a,b).

Cosmopolitan ethics and global justice can lead to successful adaptation and sustainability (Caney, 2006; Harris, 2010) and support collective decision making on public matters through voting procedures (Held, 2004). Ethics also concerns the conduct and application of research, especially research involving stakeholders. Action-based and participatory research requires that a range of ethical guidelines be followed, taking consideration of the rights of stakeholders, respect for cultural and practical knowledge, confidentiality, dissemination of results, and development of intellectual property (Macaulay et al., 1999; Kindon et al., 2007; Daniell et al., 2009; Pearce et al., 2009). Ethical agreements and processes are an essential part of participatory research, whether taking part as behavioral change processes promoting adaptation or projects of collaborative discovery (*high confidence*). Although the climate change ethics literature is rapidly developing, the related practice of decision making and implementation needs further development. Ethical and equity issues are discussed in WGIII AR5 Chapter 3.

2.2.2. Institutional Context

2.2.2.1. Institutions

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction (North, 1990; Glossary). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame (Young et al., 2008). Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization (Glossary). Virtually all CIAV decisions will be made by or influenced by institutions because they shape the choices made by both individuals and organizations (Bedsworth and Hanak, 2012). Institutional linkages are important for adaptation in complex and multi-layered social and biophysical systems such as coastal areas (Section 5.5.3.2) and urban systems (Section 8.4.3.4), and are vital in managing health (Section 11.6), human security (Sections 12.5.1, 12.6.2), and poverty (Section 13.1). Institutional development and interconnectedness are vital in mediating vulnerability in social-ecological systems to changing climate risks, especially extremes (Chapters 5, 7 to 9, 11 to 13).

The role of institutions as actors in adaptation are discussed in Section 14.4, in planning and implementing adaptation in Section 15.5, and in providing barriers and opportunities in Section 16.3. Their roles can be very diverse. Local institutions usually play important roles in accessing resources and in structuring individual and collective responses (Agarwal, 2010; see also Section 14.4.2) but Madzwamuse (2010) found that in Africa, state-level actors had significantly more influence on formal adaptation policies than did civil society and local communities. This suggests a need for greater integration and cooperation among institutions of all levels (Section 15.5.1.2). Section 14.2.3 identifies four institutional design issues: flexibility; potential for integration into existing policy plans and programs; communication, coordination, and cooperation; and the ability to engage with multiple stakeholders.

Institutions are instrumental in facilitating adaptive capacity, by utilizing characteristics such as variety, learning capacity, room for autonomous change, leadership, availability of resources, and fair governance (Gupta et al., 2008). They play a key role in mediating the transformation of coping capacity into adaptive capacity and in linking short and long-term responses to climate change and variability (Berman et al., 2012). Most developing countries have weaker institutions that are less capable of managing extreme events, increasing vulnerability to disasters (Lateef, 2009; Biesbroek et al., 2013). Countries with strong functional institutions are generally assumed to have a greater capacity to adapt to current and future disasters. However, Hurricane Katrina of 2005 in the USA and the European heat wave of 2003 demonstrate that strong institutions and other determinants of adaptive capacity do not necessarily reduce vulnerability if these attributes are not translated to actions (IPCC, 2007a; see also Box 2-1, Section 2.4.2.2).

To facilitate adaptation under uncertainty, institutions need to be flexible enough to accommodate adaptive management processes such as evaluation, learning, and refinement (Agarwal, 2010; Gupta et al., 2010; see also Section 14.2.3). Organizational learning can lead to significant change in organizations' purpose and function (Bartley, 2007), for example, where non-governmental organizations have moved from advocacy to program delivery with local stakeholders (Ziervogel and Zermoglio, 2009; Kolk and Pinkse, 2010; Worthington and Pipa, 2010).

Boundary organizations are increasingly being recognized as important to CIAV decision support (Guston, 2001; Cash et al., 2003; McNie, 2007; Vogel et al., 2007). A boundary organization is a bridging institution, social arrangement, or network that acts as an intermediary between science and policy (Glossary). Its functions include facilitating communication between researchers and stakeholders, translating science and technical information, and mediating between different views of how to interpret that information. It will also recognize the importance of location-specific contexts (Ruttan et al., 1994); provide a forum in which information can be co-created by interested parties (Cash et al., 2003); and develop boundary objects, such as scenarios, narratives, and model-based decision support systems (White et al., 2010). Adaptive and inclusive management practices are considered to be essential, particularly in addressing wicked problems such as climate change (Batie, 2008). Boundary organizations also link adaptation to other processes managing global change and sustainable development.

Boundary organizations already contributing to regional CIAV assessments include the Great Lakes Integrated Sciences and Assessments Center in the USA (GLISA; http://www.glisa.umich.edu/); part of the Regional Integrated Sciences and Assessments Program of the U.S. government (RISA; Pulwarty et al., 2009); the UK Climate Impacts Program (UKCIP; UK Climate Impacts Program, 2011); the Alliance for Global Water Adaptation (AGWA; http://alliance4water.org); and institutions working on water issues in the USA, Mexico, and Brazil (Kirchhoff et al., 2012; Varady et al., 2012).

2.2.2.2. Governance

Effective climate change governance is important for both adaptation and mitigation and is increasingly being seen as a key element of risk management (*high confidence*) (Renn, 2008; Renn et al., 2011). Some analysts propose that governance of adaptation requires knowledge of anticipated regional and local impacts of climate change in a more traditional planning approach (e.g., Meadowcroft, 2009), whereas others propose governance consistent with sustainable development and resilient systems (Adger, 2006; Nelson et al., 2007; Meuleman and in 't Veld, 2010). Quay (2010) proposes "anticipatory governance"—a flexible decision framework based on robustness and learning (Sections 2.3.3, 2.3.4). Institutional decisions about climate adaptation are taking place within a multi-level governance system (Rosenau, 2005; Kern and Alber, 2008). Multi-level governance could be a barrier for successful adaptation if there is insufficient coordination as it comprises different regulatory, legal, and institutional systems (Section 16.3.1.4), but is required to manage the "adaptation paradox" (local solutions to a global problem), unclear ownership of risks and the adaptation bottleneck linked to difficulties with implementation (Section 14.5.3). Lack of horizontal and vertical integration between organizations and policies leads to insufficient risk governance in complex social-ecological systems such as coasts (Section 5.5.3.2) and urban areas (Section 8.4), including in the management of compound risks (Section 19.3.2.4).

Legal and regulatory frameworks are important institutional components of overall governance, but will be challenged by the pervasive nature of climate risks (*high confidence*) (Craig, 2010; Ruhl, 2010a,b). Changes proposed to manage these risks better under uncertainty include integration between different areas of law, jurisdictions and scale, changes to property rights, greater flexibility with respect to adaptive management, and a focus on ecological processes rather than preservation (Craig, 2010; Ruhl, 2010a; Abel et al., 2011; Macintosh et al., 2013). Human security in this report is not seen just as an issue of rights (Box 12-1), given that a minimum set of universal rights exists (though not always exercised), but is instead assessed as being subject to a wide range of forces. Internationally, sea level rise could alter the maritime boundaries of many nations that may lead to new claims by affected nations or loss of sovereignty (Barnett and Adger, 2003). New shipping routes, such as the North West Passage, will be opened up by losses in Arctic sea ice (Sections 6.4.1.6, 28.2.6). Many national and international legal institutions and instruments need to be updated to face climate-related challenges and decision implementation (*medium confidence*) (Verschuuren, 2013).

2.3. Methods, Tools, and Processes for Climate-related Decisions

This section deals with methods, tools, and processes that deal with uncertainties (Section 2.3.1); describes scenarios (Section 2.3.2); covers trade-offs and multi-metric valuation (Section 2.3.3); and reviews learning and reframing (Section 2.3.4).

2.3.1. Treatment of Uncertainties

Most advice on uncertainty, including the latest guidance from the IPCC (Mastrandrea et al., 2010; see also Section 1.1.2.2), deals with uncertainty in scientific findings and to a lesser extent confidence. Although this is important, uncertainty can invade all aspects of decision making, especially in complex situations. Whether embodied in formal analyses or in the training and habits of decision makers, applied management is often needed because unaided human reasoning can produce mismatches between actions and goals (Kahneman, 2011). A useful high-level distinction is between ontological uncertainty—what we know—and epistemological uncertainty—how different areas of knowledge and "knowing" combine in decision making (van Asselt and Rotmans, 2002; Walker et al., 2003). Two other areas of relevance are ambiguity (Brugnach et al., 2008) and contestedness (Klinke and Renn, 2002; Dewulf et al., 2005), commonly encountered in wicked problems/systemic risks (Renn and Klinke, 2004; Renn et al., 2011).

Much of this uncertainty can be managed through framing and decision processes. For example, a predict-then-act framing is different to an assess-risk-of-policy framing (SREX Section 6.3.1 and Figure 6.2; Lempert et al., 2004). In the former, also known as "top-down," model or impacts-first, science-first, or standard approach, climate or impact uncertainty is described independently of other parts of the decision problem. For instance, probabilistic climate projections (see Figure 21-4 or WGI AR5 Chapters 11 and 12; Murphy et al., 2009) are generated for wide application, and thus are not tied to any specific choice. This follows the cause and effect model described in Section 2.1. The basic structure of IPCC Assessment Reports follows this pattern, with WGI laying out what is known and uncertain about current and future changes to the climate system. Working Groups II and III then describe impacts resulting from and potential policy responses to those changes (Jones and Preston, 2011).

In contrast, the "assess-risk-of-policy" framing (Lempert et al., 2004; UNDP, 2005; Carter et al., 2007; Dessai and Hulme, 2007) starts with the decision-making context. This framing is also known as "context-first" (Ranger et al., 2010); "decision scaling" (Brown et al., 2011); "bottom-up"; vulnerability, tipping point (Kwadijk et al., 2010); critical threshold (Jones, 2001); or policy-first approaches (SREX Section 6.3.1). In engaging with decision makers, the "assess-risk-of-policy" approach often requires information providers work closely with decision makers to understand their plans and goals, before customizing the uncertainty description to focus on those key factors. This can be very effective, but often needs to be individually customized for each decision context (Lempert and Kalra, 2011; Lempert, 2012) requiring collaboration between researchers and users (see Box 2-1). A "predict-then-act" framing is appropriate when uncertainties are shallow, but when uncertainties are deep, an "assess-risk-of-policy" framing is more suitable (Dessai et al., 2009).

The largest focus on uncertainty in CIAV has been on estimating climate impacts such as streamflow or agricultural yield changes and their consequent risks. Since AR4, the treatment of these uncertainties has advanced considerably. For example, multiple models of crop responses to climate change have been compared to estimate inter-model uncertainty (Asseng et al., 2013). Although many impact studies still characterize uncertainty by using a few climate scenarios, there is a growing literature that uses many climate realizations and also assesses uncertainty in the impact model itself (Wilby and Harris, 2006; New et al., 2007). Some studies propagate uncertainties to evaluate adaptation options locally (Dessai and Hulme, 2007) by assessing the robustness of a water company's plan to climate change uncertainties or regionally (Lobell et al., 2008) by identifying which regions are most in need of adaptation to food security under a changing climate. Alternatively, the critical threshold approach, where the likelihood of a given criterion can be assessed as a function of climate change, is much less sensitive to input uncertainties than assessments estimating the "most likely" outcome (Jones, 2010). This is one of the mainstays of robustness assessment discussed in Section 2.3.3.

2.3.2. Scenarios

A scenario is a story or image that describes a potential future, developed to inform decision making under uncertainty (Section 1.1.3). A scenario is not a prediction of what the future will be but rather a description of how the future might unfold (Jäger et al., 2008). Scenario use in the CIAV research area has expanded significantly beyond climate into broader socioeconomic areas as it has become more mainstream (*high confidence*) (Sections 1.1.3, 2.4.2.1). Climate change has also become a core feature of many scenarios used in regional and global assessments of environmental and socioeconomic change (Carpenter et al., 2005; Raskin et al., 2005). Scenarios can be used at a number of stages within an assessment process or can underpin an entire assessment. They serve a variety of purposes, including informing decisions under uncertainty, scoping and exploring poorly understood issues, and integrating knowledge from diverse domains (Parson et al., 2007; Parson, 2008).

Scenarios also contribute to learning and discussion, facilitate knowledge exchange, and can be expressed using a range of media. Local scale visualization of impacts and adaptation measures, depicted on realistic landscapes, is an emerging technology that is being tested to support dialog on adaptation planning at the local scale (Schroth et al., 2011; Sheppard, 2012). Although visual representations of scenario-based impact assessments may be available for a location, scenario-based adaptation assessments usually are not. Artistic depictions of potential adaptation measures and outcomes are being negotiated and assessed with local stakeholders in communities within Metro Vancouver, Canada (Shaw et al., 2009; Burch et al., 2010; Sheppard et al., 2011).

Climate, socioeconomic, or other types of scenarios are widely used to assess the impacts of climate change. Fewer studies report on the use of scenarios as participatory tools to enable decision making on adaptation (e.g., Harrison et al., 2013). However, the scenario literature emphasizes the importance of process over product. The new generation of climate and socioeconomic scenarios being developed from the Representative Concentration Pathways (RCPs; 1.1.3.1) and Shared Socioeconomic Pathways (SSPs; 1.1.3.2), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012) have yet to be applied within CIAV studies in any substantive way (van Ruijven et al., 2013; Ebi et al., 2014).

By separating risks into simple and systemic or wicked-problem risks, scenario needs for decision making can be better identified (*medium confidence*). For simple risks, if probabilities cannot be easily calculated then scenarios can be used to explore the problem, test for acceptable or unacceptable levels of risk, and illustrate alternative solutions for evaluation and testing. Wicked problems will need to be thoroughly scoped to select the most suitable decision-making process, with scenarios playing an important role. They may require separate applications of problem (exploratory or descriptive) and solution-based (normative or positive) scenarios or the development of reflexive scenarios, the latter being updated with new knowledge over time that may re-examine values and goals (van Notten, 2006; Wilkinson and Eidinow, 2008; Jones, 2012); these categories can also be structured as top-down, bottom-up, and interactive (Berkhout et al., 2013). Even if conditional probabilities can be used to illustrate climate futures, scenarios are needed to explore the solutions space involving strategic actions, options planning, and governance using process and goal-oriented methods (*high confidence*).

2.3.3. Evaluating Trade-offs and Multi-metric Valuation

Decision makers bring diverse aims, interests, knowledge, and values to CIAV decision making. With effective decision support, parties to a decision can manage competing views by more clearly articulating their goals; understanding how various options affect trade-offs between goals; and making informed choices that participants regard as legitimate, salient, and credible (*high confidence*) (Cash et al., 2003). The decision theory, risk governance, and ethical reasoning literatures use two broad sets of criteria for decision making: outcome-based criteria focus on whether a decision is likely to meet specified goals; process-based criteria compare alternative actions according to the process by which a decision is arrived. In particular, decision process aims to help stakeholders choose between the risks, costs, and obligations being proposed (Morgan et al., 1990), including specified levels of risk tolerance. Such choices around risk tolerance, including acceptable levels of risk, are ethical choices (DesJardins, 2012; Nanda, 2012). Selection strategies informing context and process are described in Section 14.3.5. Decision criteria inform the discussions of adaptation options, planning, and economics in Chapters 14 to 17 and WGIII AR5 Chapter 2.

Multi-attribute decision theory (Keeney and Raiffa, 1993), or multi-criteria decision analysis (MCDA), provides the most general framework for assessing outcomes-based criteria. MCDA concepts and tools organize and display the implications of alternative decisions on differing objectives (e.g., cost and environmental quality), order and test preferences among trade-offs between potentially incommensurate objectives, and show how alternative processes for choosing options can lead to different decisions. Cost-benefit analysis under uncertainty, one key tool for evaluating trade-offs, is described in Section 17.3.2.1. Simple MCDA tools include scorecards that graphically display how alternative policy choices affect different goals. For example, the "burning embers" diagram displays how risks to various attributes (e.g., health of unique systems, extreme weather events) depend on targets for a given global mean temperature increase (Figure 19-5). More sophisticated MCDA tools can optimize a portfolio of choices in a variety of ways; for example, one recent method applies scenarios representing significant uncertainty to optimize between four or more choices in order to identify robust combinations and system vulnerabilities (Kasprzyk et al., 2013). Successful use of MCDA in CIAV decisions include the U.S. Bureau of Reclamation helping stakeholders with diverse interests and values to consider 26 alternative performance measures for the Colorado River system, to agree on potential climate-related risks, and to consider options for reducing those risks. Trade-offs also occur where adaptation measures produce negative impacts in other areas of value—for example, where adaptation in agricultural and urban areas negatively affect ecosystems (Section 4.3.3.3). Korteling et al. (2013) assess the robustness of adaptation options for six criteria including risk of water shortage, environmental impact, local self-sufficiency, cost, carbon footprint, and social acceptability. Chapter 17 describes many criteria commonly used in MCDA analyses.

Robustness is often nominated as the most appropriate criterion for managing large decision uncertainty. It is a satisficing (sufficient rather than optimal) criterion (Rosenhead, 1989) that seeks decisions likely to perform well over a wide range of plausible climate futures, socioeconomic trends, and other factors (Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Robust decisions often perform better than other methods if the future turns out differently than expected. Testing for robustness can often illuminate trade-offs that help decision makers achieve consensus even when they have different future expectations. Robust choices often trade some optimality for being able to manage unanticipated outcomes. Many forms of the precautionary principle are consistent with robustness criteria (Lempert and Collins, 2007). Flexible and reversible options are often needed to manage situations with significant potential for unanticipated outcomes and differences in values and interests among decision makers (Gallopín, 2006; Hallegatte, 2009; see also Sections 2.3.4, 5.5.3.1). Flexibility is signaled by reaching of specific management thresholds, critical control points, or design states (Box 5-1). The literature disagrees on the relationship between robustness and resilience (Folke, 2006). Chapter 20 describes resilience as a property of systems that might be affected by decision makers' choices, while robustness is a property of the choices made by those decision makers (SREX Chapter 1).

Process-based criteria focus on the credibility and legitimacy of a decision process. Institutional (Section 2.2.2) and cultural and ethical (Section 2.2.1) contexts will strongly influence the appropriateness and importance of such criteria in a given situation (*high confidence*). Process criteria provide institutional rules, and governance for decision making in a wide range of circumstances (Dietz and Stern, 2008; Sen, 2009). For instance, many environmental laws require advanced notice and periods of public comment before any regulations are issued. Water rights can be made tradable, giving users extra flexibility during times of water shortage or oversupply. Participants may regard any decision that fails to respect such rights as illegitimate. In complex situations of a collaborative nature, both outcome and process-related criteria will be needed in a decision-making process (*high confidence*).

Stakeholder involvement is a central process for climate-related decision making and since the AR4 has grown in importance, particularly for adaptation decision making (e.g., Lebel et al., 2010), covering methods (Debels et al., 2009; Gardner et al., 2009; Salter et al., 2010; André et al., 2012) and reflecting concrete experiences with stakeholder involvement in CIAV assessments and adaptation processes (de la Vega-Leinert et al., 2008; Ebi and Semenza, 2008; Posthumus et al., 2008; Raadgever et al., 2008; Tompkins et al., 2008a,b; Preston et al., 2009). Lebel et al. (2010) differentiate six advantages of social learning and stakeholder involvement for adaptation to climate change: (1) reduces informational uncertainty; (2) reduces normative uncertainty; (3) helps to build consensus on criteria for monitoring and evaluation; (4) can empower stakeholders to influence adaptation and take appropriate actions themselves by sharing knowledge and responsibility in participatory processes; (5) can reduce conflicts and identify synergies between adaptation activities of various stakeholders, thus improving overall chances of success; and (6) can improve the likely fairness, social justice, and legitimacy of adaptation decisions and actions by addressing the concerns of all relevant stakeholders. Complex settings will require a detailed mapping of stakeholder roles and responsibilities (André et al., 2012).

2.3.4. Learning, Review, and Reframing

Effective decision support processes generally include learning, where learning and review become important to track decision progress (National Research Council, 2009b; see also Box 2-1, Figure 2-1). This can be achieved by developing an ongoing monitoring and review process

Frequently Asked Questions

FAQ 2.2 | Which is the best method for climate change decision making/assessing adaptation?

No single method suits all contexts, but the overall approach used and recommended by the IPCC is iterative risk management. The International Standards Organization defines risk as the effect of uncertainty on objectives. Within the climate change context, risk can be defined as the potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk management is a general framework that includes alternative approaches, methodologies, methods, and tools. Although the risk management concept is very flexible, some methodologies are quite prescriptive—for example, legislated emergency management guidelines and fiduciary risk. At the operational level, there is no single definition of risk that applies to all situations. This gives rise to much confusion about what risk is and what it can be used for.

Simple climate risks can be assessed and managed by the standard methodology of making up the "adaptation deficit" between current practices and projected risks. Where climate is one of several or more influences on risk, a wide range of methodologies can be used. Such assessments need to be context-sensitive, to involve those who are affected by the decision (or their representatives), to use both expert and practitioner knowledge, and to map a clear pathway between knowledge generation, decision making, and action.

during the scoping stage of a project or program. If circumstances change so much that desired outcomes may not be achieved, then reframing of the decision criteria, process, and goals may be required. This iterative approach begins with the many participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, then revisiting the objectives and choices based on that information (Figure 2-1). Again, process is important. Pelling et al. (2008) found that accounting for different personal values in both an official and informal capacity could enhance social learning and therefore adaptive capacity. Measuring progress on adaptation and adaptive capacity by tracking impacts, vulnerability, and related adaptation metrics and process indicators is discussed in Section 14.6. Such metrics are needed to transfer wider learning on adaptation to new situations.

Learning and review can range from periodic reporting to adaptive management. Adaptive management refers to a choice of policy required to generate reliable new information (Holling, 1978, 1996) and involves a process of adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables (Glossary). Adaptive strategies are designed to be robust over a wide range of futures by evolving over time in response to new information (Rosenhead, 1989; Walker et al., 2001; Lempert and Schlesinger, 2002; Swanson et al., 2006). Necessary components include separating immediate actions from those that can be deferred (and that may require additional information); an explicit process to generate new information; institutional mechanisms for incorporating and acting on new information; and some understanding of the policy limits that, if exceeded, should lead to its re-evaluation (Swanson et al., 2012; see also Box 5-1). As indicated by Figure 2-1, effective decision making not only requires flows of appropriate information but people willing and able to act on it. Though most policies change over time, very few follow the steps of an intentional adaptive strategy (*high confidence*). For instance, McCray et al. (2010) surveyed 32 examples of U.S. environmental, health, and safety regulations—all legally required to be adaptive—and found only five instances where any policy change occurred as intended.

Reframing of an action can occur when an existing set of decisions and actions are failing to manage risks adequately (see Box 2-1). Based on experience to date, there now exists a sufficiently rich set of available methods, tools, and processes to support effective CIAV decisions in a wide range of contexts (*medium confidence*), although they may not be combined appropriately, accessible, or readily used by decision makers (Webb and Beh, 2013). Tools for decision making, planning and development, and transfer and diffusion are discussed in Section 15.4.

2.4. Support for Climate-related Decisions

Growing understanding of the aspects of decision making (Section 2.2) and methods and tools (Section 2.3) have led to improved support for CIAV decisions, as shown by the provision of climate information and services (Section 2.4.1), methods for impacts and vulnerability assessments (Section 2.4.2), and decision support in practice (Section 2.4.3). Figure 2-3 divides the decision-making process into four stages: scoping, analysis, implementation and review, outlining institutional, leadership, knowledge, and information characteristics for each stage. Most effort in CIAV research has been put into the first two stages, whereas decision implementation and follow-up have been minimal. This does not imply that the analysis stage is discounted. Problem analysis and solution evaluation are significant undertakings in any decision process, but that is where most current climate change assessments stop. Note that each of these stages can be divided into other quite distinct process elements.

2.4.1. Climate Information and Services

Climate services are institutions that bridge generation and application of climate knowledge. History and concepts are described in Section

Box 2-1 | Managing Wicked Problems with Decision Support

A well-designed decision support process, combined with favorable political conditions, can effectively address "wicked" (Section 2.1) decision challenges. The State of Louisiana faces a serious problem of coastal land loss, exposing the region's fisheries and heightening the risk of storm surge damage to the City of New Orleans, one of the USA's largest ports with facilities that account for ~20% of U.S. oil and gas production (Coastal Protection and Restoration Authority, 2007). Previous efforts at comprehensive coastal protection had been stymied by, among other factors, numerous competing jurisdictions and stakeholders with a wide range of conflicting interests.

In the aftermath of Hurricane Katrina, the state embarked on a new coastal planning effort, this time with extensive decision support. The Coastal Protection and Restoration Authority organized an extension decision support effort with a network of research institutions interacting with a 33-member stakeholder group consisting of representatives from business and industry; federal, state, and local governments; non-governmental organizations; and coastal institutions. In dozens of workshops over the course of 2 years, these stakeholders influenced the development of and interacted with a decision support system consisting of (1) a regional model that integrated numerous strands of scientific data into projections of future flood risk (Fischbach et al., 2012) and (2) a multi-attribute planning tool that allowed stakeholders to explore the implications of alternative portfolios of hundreds of proposed risk reduction projects over alternative sea level rise scenarios (Groves et al., 2012). This decision support system allowed decision makers and stakeholders to first formulate alternative risk reduction plans then to visualize outcomes and trade-offs up to 50 years into the future.

The resulting Master Plan for a Sustainable Coast passed the state legislature by a unanimous vote in May 2012. Deviating strongly from past practice, the plan allocates far more resources to restoring natural barriers than to structural measures such as levees. The plan balances the interests of multiple stakeholders and contains some projects that offer near-term benefits and some whose benefits will be largely felt decades from now. Observers recognized that extensive analytic decision support contributed significantly to this plan.

2.4.1.1, how decision support applied in Section 2.4.1.2, and the policy implications of climate services as a global practice in Section 2.4.1.3. These institutions supply climate information on local, regional, national, and global scales for the monitoring of risks, mitigation, and adaptation planning as an important component of sustainable development (Sivakumar et al., 2011). The Global Framework for Climate Services (Hewitt et al., 2012) aims to "enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy, and practice on the global, regional, and national scale" (http://www.wmo.int/pages/gfcs/index_en.php). Climate services focus on the connection between climate science and the public demand for information; however, their development and deployment needs support from many other disciplines (Miles et al., 2006). This extended reach requires measures such as case-specific communication, engagement, and knowledge exchange skills (*high confidence*).

While many countries have already established national and regional climate services or are on the way to doing so, they show significant differences. The development of Regional Climate Services in the USA and parts of Europe, with their increasing focus on communication and decision support, is well documented (DeGaetano et al., 2010; von Storch et al., 2011). Developing countries are becoming increasingly aware of the need for climate services (Semazzi, 2011), which is in part reflected in the migration of regional climate models into those countries. In 2001 only around 21 (mostly Organisation for Economic Co-operation and Development (OECD)) countries were running regional climate models (RCMs), but today more than 100 countries are trained in using the Providing REgional Climates for Impact Studies (PRECIS) RCM (Jones et al., 2004; Edwards, 2010). Regional climate services are expanding geographically, shifting from simple understandings of climate cause and effect to ever more complex and wicked problem situations and are becoming more interdisciplinary.

2.4.1.1. Climate Services: History and Concepts

Early climate services in North America were seen as an expansion of weather services, dealing mainly with forecasts, seasonal outlooks, and risk assessment in a mostly stationary but variable climate (Changnon et al., 1990; Miles et al., 2006; DeGaetano et al., 2010). This mainly technical outlook had limited effectiveness; for example, decision makers had difficulties understanding and using climate data for planning purposes (Changnon et al., 1990; Miles et al., 2006; Visbeck, 2008) and the data were slow to access and of poor quality (Changnon et al., 1990). As these services developed, formal definitions of their mission and scope shifted to being user-centric, focusing on active research, data stewardship and effective partnership (National Research Council, 2001). Climate services were understood as a clearinghouse and technical access point to stakeholders, providing education and user access to experts—the latter informing the climate forecast community of information needs, largely to inform adaptation (Miles et al., 2006).

Downscaling is a key product demanded by users for decision making (Section 21.3.3.2). For example, in Africa, regional climate models play an increasing role in Regional Climate Outlook Forums arranged by the

2

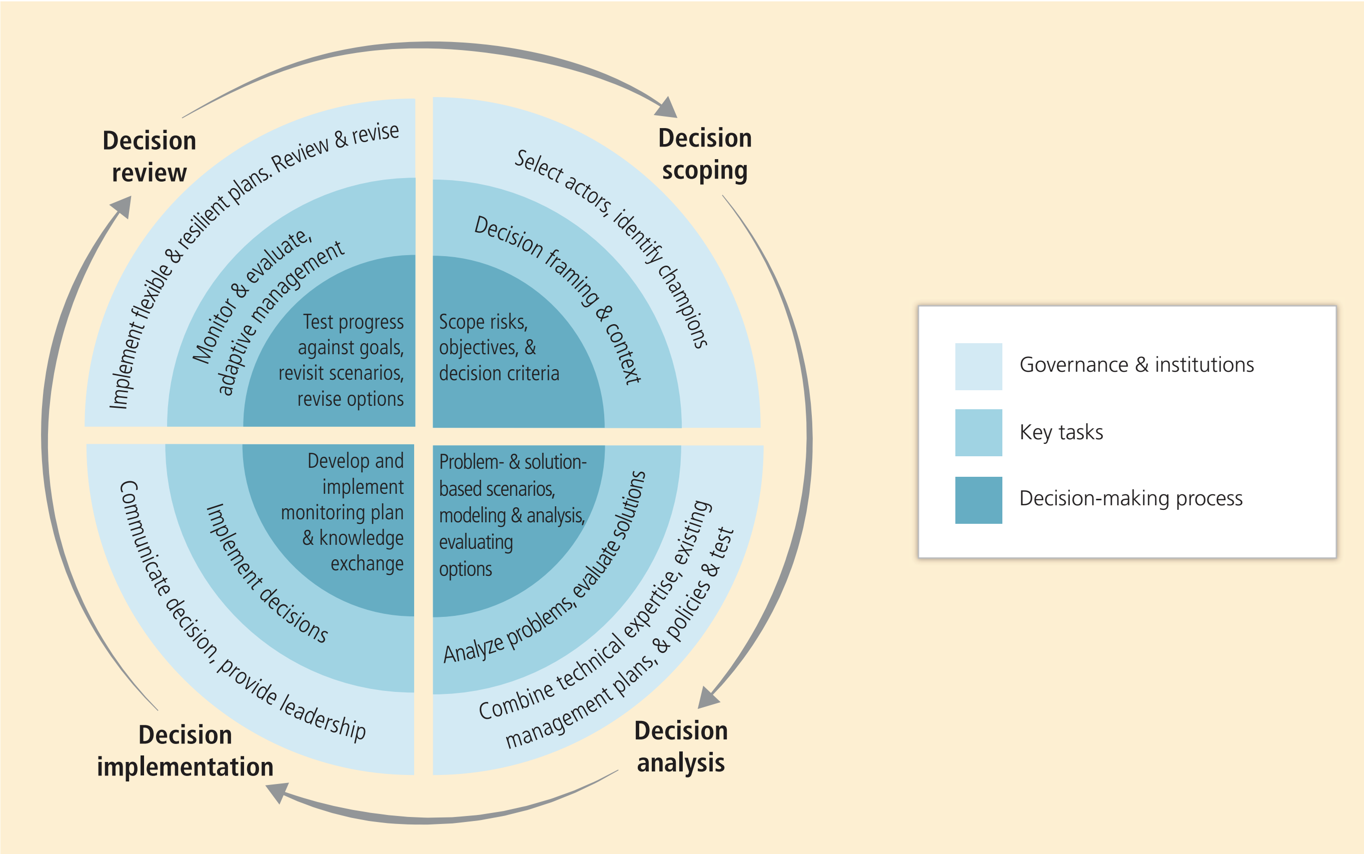


Figure 2-3 | Four-stage process of decision making. Note that while adaptive management is located in the decision review quadrant here, when applied it will influence the entire process.

World Meteorological Organization (WMO). The Global Framework for Climate Services was created in order to coordinate and strengthen activities and develop new infrastructure where needed, focusing on developing countries (WMO, 2011; Hewitt et al., 2012). From initially being supply-focused and static, public climate services increasingly need communication skills, engagement, and knowledge exchange in a highly challenging environment of technical and institutional networks, monitoring systems, and collaborations with other institutions, stakeholders, and decision makers (DeGaetano et al., 2010).

2.4.1.2. Climate Services: Practices and Decision Support

Decision support is generally acknowledged as an integral part of climate services (*high confidence*) (Miles et al., 2006; DeGaetano et al., 2010). Depending on the stage and context in question (see Section 2.1.3.), "best" data as framed by experts should be reconciled with user needs in order to produce scientific information that is relevant and suitable for decision making. Social and cultural determinants have to be taken into account (see Section 2.2) and require the communication of scientific data to be context-specific. Decision support for climate services consists of "processes of interaction, different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at any stage in the policy- or decision-making process" (Moser, 2009, p. 11). The climate service is a "process of two-way communication" and "involves providing context that turns data into information" (Shafer, 2004). Capacity building is required on all sides of the communication process. For regional climate services, a successful learning process engages both users and providers of knowledge in knowledge exchange. For example, the uptake and utility of climate forecasts in rural Africa is described in Box 9-4.

As knowledge brokers, climate services have to establish an effective dialog between science and the public (von Storch et al., 2011). This dialog undertakes two main tasks: One is to understand the range of perceptions, views, questions, needs, concerns, and knowledge in the public and among stakeholders about climate, climate change, and climate risks; the other task is to convey the content of scientific knowledge to the public, media, and stakeholders. This includes communicating the limitations of such knowledge, the known uncertainties, and the unknowable, as well as the appropriate role of science in complex decision processes (von Storch et al., 2011).

2.4.1.3. The Geo-political Dimension of Climate Services

Climate knowledge is continually being documented and assessed by the social sciences within a policy-relevant context (Yearley, 2009; Grundmann and Stehr, 2010). One focus is on the spread of climate knowledge into developing countries. Climate models distributed to users with no in-house capacity for model development build capacity in regional climate science, producing high-resolution data for local decision making. This mobility of knowledge has far-reaching implications for how climate knowledge is produced; strengthening the influence of epistemic communities such as the IPCC and other global governance mechanisms (Mahony and Hulme, 2012). Thus, while regional climate models play an increasingly important role in decision-making processes, critics argue that climate monopolizes planning and development strategies, rendering other forms of knowledge subordinate to this "climate reductionism" (Dessai et al., 2009; Hulme, 2011).

Indigenous forms of knowledge—including the specialized knowledge of any stakeholder—are becoming increasingly relevant for climate services (*high confidence*) (Strauss and Orlove, 2003; Crate and Nuttal, 2009; Crate, 2011; Ulloa, 2011; Krauss and von Storch, 2012). Local forms of knowledge and scientific climate models are not necessarily mutually exclusive; individual case studies show how both forms of knowledge contribute jointly to place-based adaptation (Strauss and Orlove, 2003; Orlove and Kabugo, 2005; Orlove, 2009; Strauss, 2009; Orlove et al., 2010). Indigenous knowledge in the form of oral histories and other traditional knowledge are being compared or combined with remote sensing technologies and model-based scenarios to co-produce new knowledge, and to create a new discourse on adaptation planning (Nakashima et al., 2012; see also Table 15-1). The challenge will be to collaborate in a way that enables their integration into a shared narrative on future adaptation choices.

These examples show that adaptation needs both to be implemented locally and to be informed by larger scale (inter-)national policies and directions. One strategy will not suit every location. Endfield (2011) argues for a "reculturing and particularizing of climate discourses" in order to successfully localize global and scientific meta-narratives. Climate service development combines very different types of knowledge and the social, cultural, and communication sciences play a decisive role in this process (Pidgeon and Fischhoff, 2011; von Storch et al., 2011). To position itself and to react according to the diverse demands, science-based climate services have to become "rooted in society" (Krauss, 2011). The climate science community does not necessarily take the lead, but becomes part of an inter- and trans-disciplinary process, where politics, culture, religion, values, and so forth become part of climate communication (*medium confidence*).

2.4.2. Assessing Impact, Adaptation, and Vulnerability on a Range of Scales

CIAV assessments address the "adapt to what" question, which can enable a dialog among practitioners, stakeholders, and the public on planning and implementation of adaptation measures within prevailing mechanisms for governance. To date, however, assessments have focused more on I than A (see Figure 1-1d). A number of global initiatives are taking place to enable knowledge generation, transfer, and use, including the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA; http://www.provia-climatechange.org/), the Nairobi Work Programme on impacts, vulnerability, and adaptation to climate change (http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php), and work by the World Bank and regional development banks (http://climatechange.worldbank.org/).

2.4.2.1. Assessing Impacts

For scenario-based impact assessments to contribute to vulnerability and risk assessment, a series of translations need to be performed. Scenarios of projected GHG concentrations are converted to changes in climate, impacts are assessed, perhaps with autonomous adaptation, leading to the evaluation of various adaptation options. This series of translations requires the transformation of data across various scales of time and space, between natural and social sciences, utilizing a wide variety of analytical tools representing areas such as agriculture, forestry, water, economics, sociology, and social-ecological systems. Climate scenarios are translated into scenarios or projections for biophysical and socioeconomic impact variables such as river flow, food supply, coastal erosion, health outcomes, and species distribution (e.g., European Climate Adaptation Platform, http://climate-adapt.eea.europa.eu). Climate services help establish and support the translation process (Section 2.4.1).

The resulting climate impacts and risks are then subject to decision making on risk management and governance. Assessments of observed events combine biophysical and socioeconomic assessments of the past and present (Table 2-1, top row). Most scenario-based assessments superimpose biophysical "futures" onto present-day socioeconomic conditions (Table 2-1, middle row). This is useful for assessing how current socioeconomic conditions may need to change in response to biophysical impacts but raises inconsistencies when future socioeconomic states are out of step with biophysical states. This will hamper assessments of future adaptation responses in coupled social-ecological systems (see Chapter 16). An important challenge, therefore, is to construct impact assessments in which biophysical futures are coupled with socioeconomic futures (Table 2-1, bottom row). A new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSPs), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012), is being developed to assist this process (Section 1.1.3.2).

A new generation of assessments links biophysical, economic, and social analysis tools in order to describe the interactions between projected biophysical changes and managed systems. For example, Ciscar et al. (2011) estimated the costs of potential climate change impacts, without public adaptation policies, in four European market sectors (agriculture, river floods, coastal areas, and tourism) and one nonmarket sector

Table 2-1 | Nature of published Impact, Adaptation, and Vulnerability (IAV) assessments.

Nature of IAV assessments	Biophysical conditions	Socioeconomic conditions
Stationarity and extrapolation	Continuation of current trends; no change in statistical properties	No change from current conditions
Transitional	Scenario-based projections of future biophysical conditions	No change from current conditions; sometimes sensitivity analysis with alternate futures
Coupled and interactive	Scenario-based projections of future biophysical conditions	Alternative futures from scenarios/storylines consistent with biophysical projections, sometimes with dynamic response

2

(human health). A similar study in the UK was conducted for tourism, health and transportation maintenance, buildings and transportation infrastructure, and residential water supplies (Hunt, 2008). In the USA, Backus et al. (2013) assessed national and state level gross domestic product (GDP) and employment impacts, incorporating direct impacts on water resources, secondary impacts on agriculture and other water interests, and indirect impacts through interstate migration of affected populations. Decision support tools are being integrated into scenario-based impact and adaptation assessments. For example, the Water Evaluation and Planning System model has been used to assess a community water system in British Columbia, Canada (Harma et al., 2012). Incorporation of stakeholder dialog processes within scenario construction (Parson, 2008) and Participatory Integrated Assessment (Salter et al., 2010) enables inclusion of local knowledge as part of scenario-based assessments.

2.4.2.2. Assessing Vulnerability, Risk, and Adaptive Capacity

The adaptation to climate change, disaster risk management, and resilience literatures all address the concept of vulnerability, defined as a susceptibility to loss or damage (Adger, 2006; Füssel, 2007), or the propensity or predisposition to be adversely affected (Glossary). Within IPCC AR4, Schneider et al. (2007) identified vulnerabilities that might be considered "key," and therefore potentially "dangerous" (see Glossary). Criteria denoting a key vulnerability include its magnitude and timing, persistence, and reversibility, and the likelihood and confidence that the contributing event(s) would occur (Sections 19.2.5, 19.6). Other criteria include the importance of a location or activity to society and society's exposure to potential loss and its capacity to adapt. Adaptive capacity has been defined as the ability to adjust, to take advantage of opportunities, or to cope with consequences (Adger et al., 2007; see also Glossary). However, adaptive capacity is context-specific, related to both availability of resources, capacity to learn, and governance measures (Gupta et al., 2010; see also Section 14.5). Actions that illustrate how adaptive capacity and climate resilience can be mutually reinforcing include disaster risk management (Sections 2.5.2, 15.3.2, 16.7.2) and "triple-win" interventions where adaptation, mitigation, and sustainable development goals are integrated so as to find climate-resilient pathways (Sections 20.3.3, 20.4.2).

The concept of an "adaptation deficit" (Burton and May, 2004) is applicable to cases such as Hurricane Katrina (Committee on New Orleans Regional Hurricane Protection Projects, 2009; Freudenberg et al., 2009; Box 2-1) or the 2003 European heat wave (Haines et al., 2006) where substantial vulnerability follows a climate event. An adaptation deficit represents a gap between an existing state of adaptation and an idealized state of adaptation where adverse impacts are avoided (Chapter 17; Glossary). The adaptation deficit has also been related to "residual impacts," which occur due to insufficient adaptation to current or future climate (IPCC, 2007a). Within developing countries, Narain et al. (2011) consider the adaptation deficit as being part of a larger "development deficit." Cardona et al. (2012) cite other "deficit" indicators, including a Disaster Deficit Index (extreme event impact combined with financial ability to cope), structural deficit (low income, high inequality, lack of access to resources, etc.), and a risk communication deficit. Maladaptation occurs where a short-term response inadvertently leads to an increase in future vulnerability (Glantz, 1988; Barnett and O'Neill, 2010; McEvoy and Wilder, 2012). Barriers unrelated to scientific knowledge can hamper effective decision making (Adger and Barnett, 2009; Berrang Ford et al., 2011). This may help to explain why some extreme events create surprising levels of damage within developed countries.

The assessment of potential future damages and loss requires approaches that link biophysical and socioeconomic futures. An example is the assessment of climate change effects on human health, including research-to-decision pathways, monitoring of social vulnerability indicators and health outcomes (English et al., 2009; Portier et al., 2010), and tools for enabling adaptive management (Hess et al., 2012). Examples of regional scale scenario-based vulnerability assessments are case studies for North Rhine-Westphalia in Germany (Holsten and Kropp, 2012) and agriculture in Mexico (Monterroso et al., 2012). An example of a larger scale study is a vulnerability assessment of ecosystem services for Europe, in which future adaptive capacity was based on indicators from the *Special Report on Emission Scenarios* (SRES) storylines (Metzger and Schröter, 2006). Difficulty in separating the relative influences of changing climate and development patterns hampers assessments of observed trends in property damage caused by atmospheric extreme events. Recent increases in economic losses may be due to changes in probabilities of extreme events, changes in human development patterns (more people in harm's way) without changes in climatic extremes, or a combination of both (Pielke, 1998; Mills, 2005; Munich Re Group, 2011). IPCC (2012) concluded that increasing exposure has been the major cause, but a role for climate change has not been excluded.

Development choices taken in the current or near term can potentially influence future vulnerability to projected climate change, hence interest in the study of emergent risks (Sections 19.3, 19.4). Interactions between development pathways, and climate change impacts and responses, could create situations with little or no precedent. Assessments based on gradual shifts in mean conditions could underestimate future risk and consequent damage, suggesting the need for process-based methodologies that focus on enhancing resilience (Jones et al., 2013; see also Sections 2.5.2, 20.2.3). An example of assessing this type of risk, and the costs and benefits of potential adaptation responses, is a resilience assessment framework for infrastructure networks (Vugrin et al., 2011; Turnquist and Vugrin, 2013).

2.4.3. Climate-Related Decisions in Practice

Implementation of adaptation actions, resilience strategies and capacity building can take place as stand-alone actions or be integrated into other management plans and strategies. Recent literature on potential climate change effects on natural resources, public health, and community planning and management is reviewed in Chapters 3 to 12. As the omplexity of management challenges increases due to climate change, development, and other pressures, a range of reflexive decision-making processes are emerging under the general topics of adaptive management, iterative risk management, and community-based adaptation (e.g., Section 5.5.4.1). However, there are few assessments of adaptation delivery and effectiveness (Section 15.6). Cross-sectoral integrated approaches such as Integrated Water Resources Management (IWRM), sustainable forestry management (SFM), and Integrated Coastal Zone Management (ICZM) are viewed as being more effective than stand-alone efforts (Section 16.5.1).

Adaptive approaches to water management can potentially address uncertainty due to climate change (Section 3.6.1) but there is a limited number of examples in practice (Section 3.6.4). Examples of recent strategies include an IWRM roadmap prepared for the state of Orissa, India (Jønch-Clausen, 2010) and seven cases in the USA (Bateman and Rancier, 2012), some of which are applying adaptive water management using a scenario-based experimental approach intending to align with IWRM and promote resilience. Adaptations in urban systems following integrated urban water management principles are becoming widespread (Section 8.3.3.4) and in rural systems are more advanced in developed countries and less so in developing countries, especially those within transboundary basins (Sections 9.4.3.2, 24.4.1.5, 24.4.2.5, 25.5.3, 26.3.3, 27.3.1.2, 27.3.2.2).

Adaptation in agriculture ranges from small adjustments made to current activities through to transformative adaptations across whole systems (Sections 7.5.1, 9.4.3.1, 22.4.5.7, 23.4.1, 24.4.4.5, 25.7.2, 26.5.4, 27.3.4.2). Diversified systems are more resilient with some diversification coming from off farm sources (Section 9.4.3.1). There are few unequivocal adaptations to climate, but the development of adaptive capacity is more widespread (Section 7.5.1.2). Adaptation in forestry has expanded since the AR4 (Section 9.4.3.3) and is aiming to develop toward SFM by focusing on biological diversity, productive and protective functions of forests, maintenance of their social and economic benefits, and governance (McDonald and Lane, 2004; Wijewardana, 2008; Montréal Process, 2009). Although SFM is still largely an abstract concept (Seppälä et al., 2009), managing climate change risks is seen as necessary for achieving its objectives (Montréal Process, 2009). Governments and companies are also considering assisted migration of forest species as an adaptation strategy (Pedlar et al., 2012) and payment for ecosystem services is becoming more common (Section 9.4.3.3). Sustainable Fisheries Management has long-term ecological and productivity goals (FAO, 2013) but climate change has generally not been included in strategic guidance for fisheries management (Brander, 2010). Ecosystem-based approaches to management (e.g., Zhou et al., 2010) and transformative approaches will be required (Sections 7.5.1.1.2, 9.4.3.4). Sustainable livelihoods approaches are also being applied for populations dependent on marine resources (Sections 9.4.3.4, 30.6.2.1; Table 30-2).

National Adaptation Programmes of Action (NAPA) for least-developed countries (LDCs) are designed to be flexible, action-oriented, and country-driven (UNFCCC, 2009). Key preparatory steps include the synthesis of available information on vulnerability and impacts via extensive public participation (see Chapter 14). The NAPA process has assisted LDCs to assess climate sensitive sectors and prioritize projects to address the most urgent adaptation issues (Lal et al., 2012; UNFCCC, 2012). Integrating NAPAs with other socioeconomic programs can help develop resilience. However, although many countries have linked their NAPAs with development programs, Hardee and Mutunga (2010) argue that they have had limited success in aligning the NAPA priorities with existing national priorities such as population growth. To this end, scaling up and institutionalization of the NAPA process has commenced. Under the Cancun Adaptation Framework, a process was established that enables LDCs to formulate and implement National Adaptation Plans (NAPs) building upon the NAPA experience (UNFCCC, 2013). The NAP's main objectives are to identify vulnerabilities and medium- and long-term adaptation needs, and to develop and implement strategies and programs to address those needs and also to mainstream climate change risks. The NAPs are also an opportunity to align with other global initiatives such as the Millennium Development Goals and Hyogo Framework for Action.

Many developed countries are developing adaptation strategy documents at different scales of governance (European Environmental Agency, 2013). Biesbroek et al. (2010) analysed National Adaptation Strategies (NAS) of nine European nations, examining their decision making aspects and finding both "top-down" and "bottom-up" (delegation of authorities to local governments) approaches. Dissemination of information on weather, climate, impacts, vulnerability, and scenarios was found to be a critical element for adaptation decision making.

Climate risk is being increasingly factored into existing decision-making processes (Section 15.2.1). For example, learning from the 2003 heat waves that killed some 35,000 people across Europe, many European countries have implemented health-watch warning systems (Alcamo et al., 2007; WHO, 2008). Vietnam has initiated large-scale mangrove restoration and rehabilitation programs with the support of international institutions to protect coastal settlements and aquaculture industry (World Resources Institute et al., 2011). The Tsho Rolpa glacier lake in Nepal was at the risk of outburst due to glacial melt (Adger et al., 2007) so the Government of Nepal introduced both short- and long-term measures to prevent the outburst flood event (World Resources Institute et al., 2011). In many ways, local government is at the coal face of adaptation decision making (Pelling et al., 2008; Measham et al., 2011; Roberts et al., 2012). Municipal governments are incorporating climate change adaptation planning within municipal planning instruments, including energy and water system design, disaster risk reduction, and sustainability plans (Ford and Berrang-Ford, 2011; Rosenzweig et al., 2011). In human health, two main areas of benefit are occurring through improvements in current health patterns being exacerbated by changing climate and in reducing pollutants associated with co-pollutants of GHG emissions (Sections 11.7, 11.9). Climate is being increasingly recognized as a component of human conflict and insecurity, so is becoming a factor in governance arrangements affecting security and peace building programs (Section 12.5).

Details of adaptation planning within urban and rural settlements are addressed in Chapters 8 and 9, respectively. In urban settlements, adaptations are occurring in areas of energy, water, transport, housing, and green infrastructure (Section 8.3.3) but opportunities for broader integration into planning and the urban economy are largely being missed (Section 8.4). The overall status of adaptation implementation is assessed in Chapter 15. Although there is a rapidly growing list of adaptation plans being generated at multiple scales, an evaluation of adaptation plans from Australia, UK, and the USA suggests they are under-developed (Berrang Ford et al., 2011). These plans reflect a preference for capacity building over delivery of specific vulnerability-reduction measures, indicating that current adaptation planning is still informal and ad hoc (Preston et al., 2011; Bierbaum et al., 2013).

Frequently Asked Questions

FAQ 2.3 | Is climate change decision making different from other kinds of decision making?

Climate-related decisions have similarities and differences with decisions concerning other long-term, high-consequence issues. Commonalities include the usefulness of a broad risk framework and the need to consider uncertain projections of various biophysical and socioeconomic conditions. However, climate change includes longer time horizons and affects a broader range of human and Earth systems as compared to many other sources of risk. Climate change impact, adaptation, and vulnerability assessments offer a specific platform for exploring long-term future scenarios in which climate change is considered along with other projected changes of relevance to long-term planning.

In many situations, climate change may lead to non-marginal and irreversible outcomes, which pose challenges to conventional tools of economic and environmental policy. In addition, the realization that future climate may differ significantly from previous experience is still relatively new for many fields of practice (e.g., food production, natural resources management, natural hazards management, insurance, public health services, and urban planning).

Capacity barriers have hampered the transition from planning to implementation, so only a small number of jurisdictions have been successful at implementing adaptation measures (Section 15.2). However, there has been growth in community-based adaptation initiatives (Baer and Risbey, 2009; Rudiak-Gould, 2011; Sections 15.1, 15.2, 15.5, 15.6).

Various enabling factors for implementation have been identified in stakeholder engagement processes. Such factors include access to resources and sharing observations, language specific information, and ICT tools (e.g., wireless sensor networks, geographic information systems and web-based tools) that increase local awareness, allowing for good public understanding of stresses, risks, and trade-offs (Section 15.4.2). These factors allow new strategies to be explored, evaluated, and implemented (Shepherd et al., 2006; Hewitt et al., 2013). Enabling factors also include customized impact and vulnerability assessments for communities of interest and local practitioners who would serve as champions for adaptation planning, and the existence of local social influences/networks and capacity that enable long-term strategic planning and mainstreaming (Gardner et al., 2009; Cohen, 2010). These factors are further discussed in Chapters 15 and 16. Local government officials often lack training on climate change adaptation and require capacity to be built in a number of areas. To assist this process, guidebooks have been produced, framing the process of adaptation planning as both a team-building and project management exercise, activities that are already part of usual practice (Snover et al., 2007; Bizikova et al., 2008; ICLEI Oceania, 2008; CARE International in Vietnam, 2009; Ayers et al., 2012). Practitioner engagement in decision "games" can offer another training resource (Black et al., 2012).

2.5. Linking Adaptation with Mitigation and Sustainable Development

2.5.1. Assessing Synergies and Trade-offs with Mitigation

Capacities to adapt to and mitigate climate change are broadly similar. Opportunities for synergies are particularly relevant for the agriculture, forestry, urban infrastructure, energy, and water sectors (Chapters 3, 4, 7 to 10). The IPCC AR4 (Klein et al., 2007) concluded that a lack of information made it difficult to assess these synergies. Assessing the synergies and trade-offs that face both adaptation and mitigation is an important goal of the new IPCC scenario process (Kriegler et al., 2012; O'Neill et al., 2014). These synergies and trade-offs between adaptation and mitigation are illustrated in Figure 2-4. The negatives associated with "adaptive emissions" or "new vulnerabilities" arising from mitigation do not necessarily mean that such measures should not be contemplated, but they do need to be assessed within a larger portfolio of actions where losses and gains have been sufficiently well quantified (Section 19.7). Limits of adaptation emphasize the different reach of adaptation and mitigation in managing climate risks (Sections 16.6, 19.7.5).

Mitigation can affect, for example, water resources (Section 3.7.2.1), terrestrial and freshwater ecosystems (Sections 4.4.4, 19.3.2.2), agriculture (Sections 19.3.2.2, 19.4.1), and livelihoods and poverty (Section 13.3.1), and will in turn be affected by changes in water resources (Section 3.7.3.2) and terrestrial ecosystems (Sections 4.3.3.1, 4.2.4.1). Adaptation actions for agriculture generally tend to reduce emissions (Section 7.5.1.4). Potential losses of human security associated with climate policy are discussed in Sections 12.5.2 and 19.4.2.2. Recent literature on potential interactions between mitigation and adaptation is reviewed in Sections 16.4.3, 19.7.1, 19.7.2, 19.7.3, 19.7.4, and 19.7.5. Chapter 20 discusses the relationship between adaptation, mitigation, and sustainable development including sustainable risk management (Section 20.3.3).

2.5.2. Linkage with Sustainable Development: Resilience

The idea that climate change response and sustainable development should be integrated within a more holistic decision framework was assessed in IPCC AR4 (Robinson et al., 2006; Klein et al., 2007; Yohe et al., 2007). Practical aspects of this integration are being tested as decision makers endeavor to incorporate adaptation measures within official long-term development plans (Section 15.3.3). A typical example is the engagement of researchers and practitioners (planners, engineers, water managers, etc.) in scenario-based exercises to build local capacity to plan for a wide range of climate outcomes (Bizikova et al., 2010). Development can yield adaptation co-benefits if climate change is factored into its design (Sections 17.2.7.2, 20.3, 20.4).

Resilience is the capacity to change in order to maintain the same identity (see Glossary) and can be assessed through participatory research (Tyler and Moench, 2012) or through system modelling. Chapter 20 examines climate-resilient pathways, which are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development while meeting the goals of the UNFCCC (Box 20-1). An example of resilience assessment at the landscape scale is in the Arctic, where local sources of important productivity and biodiversity are being mapped and their future capacity in supporting larger ecoregions under climate change is being assessed (Christie and Sommerkorn, 2012). An industry example covers the resilience analysis of supply chains, specifically petrochemical supply chains exposed to a hurricane in the southeastern USA (Vugrin et al., 2011). For urban areas, Leichenko (2011) categorize four types of urban resilience studies: (1) urban ecological resilience, (2) urban hazards and disaster risk reduction, (3) resilience of urban and regional economies, and (4) urban governance and institutions. Boyd et al. (2008) promote resilience as a way of guiding future urbanization that would be better "climatized." The Asian Cities Climate Change Resilience Network is applying a resilience planning framework, with attention given to the role of agents and institutions (Tyler and Moench, 2012).

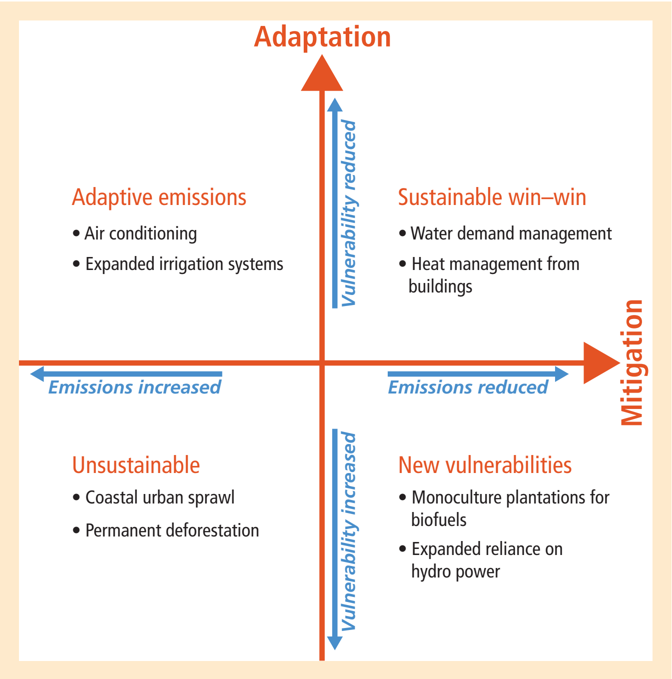


Figure 2-4 | Examples of adaptation (A): mitigation (M) trade-offs and synergies (adapted from Cohen and Waddell, 2009). The upper right quadrant (sustainable win–win) illustrates synergies in which actions enable the achievement of both adaptation and mitigation goals. The lower left quadrant (unsustainable) shows the opposite condition. The upper left (adaptive emissions) and lower right (new vulnerabilities) quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances.

Adaptive capacity is seen as an important component of resilience on a range of scales (Sections 2.1.1, 2.2.3, 2.3.4, 2.4.2, 20.3). Local cases, such as King County (Seattle) USA, illustrate the importance of researcher-practitioner collaboration for knowledge exchange (Snover et al., 2007) and iterative and reflexive processes that enable local ownership, and adjustment to new information and evaluation of actions taken (Saavedra and Budd, 2009). However, in regions with high and chronic poverty, coupled with low awareness of global change drivers, adaptation as a process is not well understood and tools that enable anticipatory learning are lacking (Tschakert and Dietrich, 2010).

The normative concept of sustainable adaptation has been proposed to manage adaptation's unintended consequences (Eriksen et al., 2011). It considers effects on social justice and environmental integrity, challenging current (unsustainable) development paths rather than seeking adjustments within them. This concept recognizes the role of multiple stressors in vulnerability, the importance of values in affecting adaptation outcomes (Section 2.2.1), and potential feedbacks between local and global processes. Little is known about the long-term effects of adaptation on livelihoods and poverty (Section 13.3.2) although focusing on poverty alleviation as part of adaptation is thought to build capacity (Sections 13.4.1, 13.4.2).

The Hyogo Framework for Action on disaster risk reduction considers climate change as an underlying risk factor, and promotes the integration of risk reduction and climate change adaptation (UNISDR, 2007, 2011; see also Section 15.3.2). Social development is being integrated with disaster risk management in order to enhance adaptive capacity and address the structural causes of poverty, vulnerability, and exposure. In small island states, this integration is being enabled through focused institutional coordination, greater stakeholder engagement, and promotion of community-based adaptation and resilience-building projects (UNISDR and UNDP, 2012). Similar initiatives are underway in urban areas (UNISDR, 2012; see also Sections 15.3.2, 15.3.3, 15.5; Chapter 24; Box CC-TC).

Resilience is also being explored as an outcome of social contracts that underpin governance. O'Brien et al. (2009) use examples from Norway, New Zealand, and Canada to illustrate how resilience thinking on climate does not easily fit into existing social contracts, and that new types of arrangements may better serve the goals of resilience and sustainable development within the context of climate change. Chapter 20 describes climate-resilient development pathways as being an explicit objective of long-term planning and decision making and considers the need for transformational adaptation aiming to achieve sustainable development (Sections 20.5).

2.5.3. Transformation: How Do We Make Decisions Involving Transformation?

Much of the existing adaptation literature examines gradual adjustment or accommodation to change. But a growing literature highlights the importance of transformative adaptation (Sections 14.3.5, 16.4.2), both in the context of a world where global temperature raise above 2°C (Kates et al., 2012; PIK, 2012) and in the context of climate-resilient pathways that manage risk through combinations of adaptation and mitigation (Section 20.5).

In concluding this chapter, we therefore reflect on some emerging, though still sparse, literature that examines such transformational adaptation, how it differs from incremental adaptation (O'Brien, 2012; Park et al., 2012), and how it might occur in specific sectors and systems (Rickards and Howden, 2012). This early literature suggests that many themes raised in this chapter may prove important to transformational adaptation, including iterative risk management with a broad view of risk, adaptive management, robustness and resilience, and deliberation (McGray et al., 2007; Leary et al., 2008; Hallegatte, 2009; Tschakert and Dietrich, 2010; Hallegatte et al., 2011; Stafford Smith et al., 2011). For instance, Irvin and Stansbury (2004) identify situations where participatory processes may be most effective for bringing about positive social and environmental change. Recently, Park et al. (2012) have proposed the Adaptation Action Cycles concept as a means to delineate incremental and transformative adaptation and the role of learning in the decision-making process. Similar to the learning process called "triple-loop"—which considers a situation, its drivers, plus the underlying frames and values that provide the situation context (Argyris and Schön, 1978; Peschl, 2007; Hargrove, 2008)—transformational adaptation may involve decision makers questioning deep underlying principles (Flood and Romm, 1996; Pelling et al., 2008) and seeking changes in institutions, such as legal and regulatory structures underlying environmental and natural resource management (Craig, 2010 ; Ruhl, 2010a), as well as in cultural values (O'Brien, 2012; O'Brien et al., 2013).

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3 Freshwater Resources

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Frequently Asked Questions

Executive Summary

Key Risks at the Global Scale

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas (GHG) concentrations (*robust evidence*, *high agreement*). {3.4, 3.5} Modeling studies since AR4, with large but better quantified uncertainties, have demonstrated clear differences between global futures with higher emissions, which have stronger adverse impacts, and those with lower emissions, which cause less damage and cost less to adapt to. {Table 3-2} For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20% (multi-model mean). By the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times greater for very high emissions (Representative Concentration Pathway 8.5 (RCP8.5)) than for very low emissions (RCP2.6) (multi-model mean) for the fixed population distribution at the level in the year 2005. {Table 3-2, 3.4.8}

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*). {3.4, 3.5} This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (*limited evidence*, *medium* to *high agreement*). {3.5.1, 3.5.2, Box CC-WE} In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing GHG concentrations and climate change remain uncertain. {Box CC-VW}

So far there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods (*limited evidence*, *medium agreement*). Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (*limited evidence*, *medium agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). Global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*). {3.2.7, 3.4.8}

Climate change is *likely* to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of the 21st century under the RCP8.5 scenario (*medium confidence*). {WGI AR5 Chapter 12} This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium evidence*, *medium agreement*). {3.4.8} Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. {3.5.1}

Climate change negatively impacts freshwater ecosystems by changing streamflow and water quality (*medium evidence*, *high agreement*). Quantitative responses are known in only a few cases. Except in areas with intensive irrigation, the streamflow-mediated ecological impacts of climate change are expected to be stronger than historical impacts owing to anthropogenic alteration of flow regimes by water withdrawals and the construction of reservoirs. {Box CC-RF, 3.5.2.4}

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (*medium evidence*, *high agreement*). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods. {3.2.5, Figure 3-2, 3.4.6, 3.5.2.3}

In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected (*robust evidence*, *high agreement*). {Table 3-1, 3.2.3, 3.2.7, 3.4.5, 3.4.6, 26.2.2} Except in very cold regions, warming in the last decades has reduced the spring maximum snow depth and brought forward the spring maximum of snowmelt discharge; smaller snowmelt floods, increased winter flows, and reduced summer low flows have all been observed. River ice in Arctic rivers has been observed to break up earlier. {3.2.3, 28.2.1.1}

Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*robust evidence*, *high agreement*). Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments. {3.4.3}

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*limited evidence*, *medium agreement*). However, increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices. {3.2.6, 3.4.7}

Adaptation, Mitigation, and Sustainable Development

Of the global cost of water sector adaptation, most is necessary in developing countries where there are many opportunities for anticipatory adaptation (*medium evidence*, *high agreement*). There is limited published information on the water sector costs of adaptation at the local level. {3.6.1, 3.6.3}

An adaptive approach to water management can address uncertainty due to climate change (*limited evidence*, *high agreement*). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. {3.6.1, 3.6.2, 3.6.4}

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (*limited evidence*, *high agreement*). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change. {3.4.5, 3.4.8, 3.5.1}

Some measures to reduce GHG emissions imply risks for freshwater systems (*medium evidence*, *high agreement*). If irrigated, bioenergy crops make water demands that other mitigation measures do not. Hydropower has negative impacts on freshwater ecosystems, which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk and soil erosion. {3.7.2.1, Box CC-WE}

3.1. Introduction

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses (Figure 3-1). Water is the agent that delivers many of the impacts of climate change to society, for example, to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, economic development, urbanization, and land use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation to climate change in the water sector can contribute to improving the availability of water.

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The observed and projected impacts of climate change on freshwater systems and their management are due mainly to increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semiarid and arid areas are particularly exposed.
- Warmer water, more intense precipitation, and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services.
- Climate change affects water management infrastructure and practice.
- Adaptation and risk management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses hydrological changes due to climate change, based mainly on research published since AR4. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I (WGI) contribution to this assessment. See WGI AR5 Chapter 4 for freshwater in cold regions and WGI AR5 Chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21 to 30. Sections 3.2.7, 3.4.8, and 3.6.3 discuss impact and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Changes Due to Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily due to anthropogenic climate change. Detection entails showing, usually statistically, that part

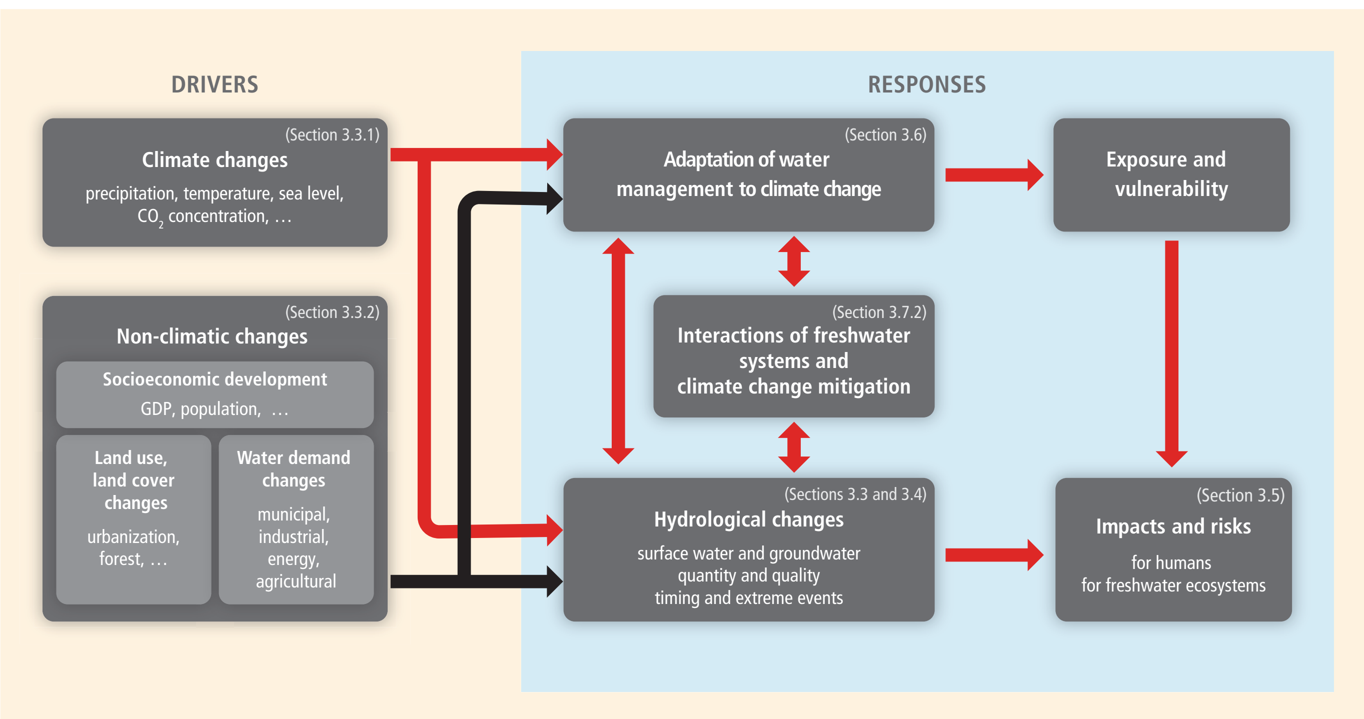
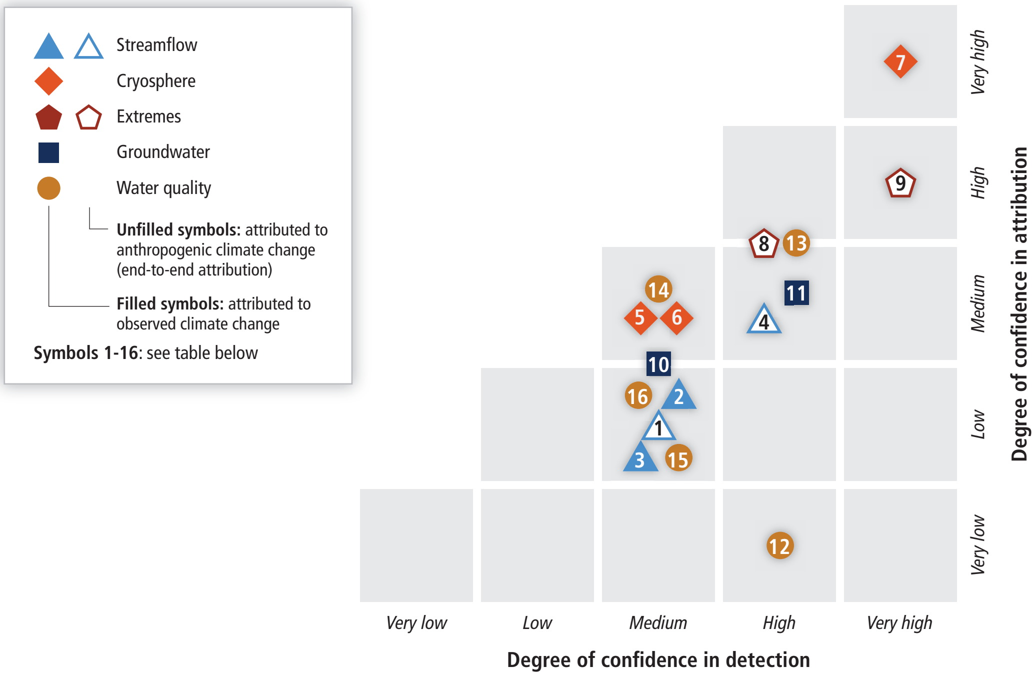


Figure 3-1 | Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).

Table 3-1 | Selected examples, mainly from Section 3.2, of the observation, detection, and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic.



	Observed change	Attributed to	Reference
1	Changed runoff (global, 1960–1994)	Mainly climatic change, and to a lesser degree CO_2 increase and land use change	Gerten et al. (2008); Piao et al. (2007); Alkama et al. (2011)
2	Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	Piao et al. (2010)
3	Earlier annual peak discharge (Russian Arctic, 1960–2001)	Increased temperature and earlier spring thaw	Shiklomanov et al. (2007)
4	Earlier annual peak discharge (Columbia River, western USA, 1950–1999)	Anthropogenic warming	Hidalgo et al. (2009)
5	Glacier meltwater yield greater in 1910–1940 than in 1980–2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	Collins (2008)
6	Decreased dry-season discharge (Peru, 1950s–1990s)	Decreased glacier extent in the absence of a clear trend in precipitation	Baraer et al. (2012)
7	Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade, 1980s–2000s	Rosenzweig et al. (2007)
8	More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic greenhouse gas emissions	Min et al. (2011)
9	Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	Pall et al. (2011)
10	Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors	Aguilera and Murillo (2009)
11	Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation	Jeelani (2008)
12	Increased dissolved organic carbon in upland lakes (UK, 1988–2003)	Increased temperature and precipitation; multiple confounding factors	Evans et al. (2005)
13	Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) episodes (Spain, 1964–1991 and 1994–2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	Marcé et al. (2010)
14	Variable fecal pollution in a saltwater wetland (California, 1969–2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	Pednekar et al. (2005)
15	Nutrient flushing from swamps, reservoirs (North Carolina, 1978–2003)	Hurricanes	Paerl et al. (2006)
16	Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature	Tibby and Tiller (2007)

of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI AR5 Chapter 10). For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human contributions such as water withdrawals, land use change, and pollution mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic drivers (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is "switched off." However, climate models do not currently simulate the water cycle at fine enough resolution for attribution of most catchment-scale hydrological impacts to anthropogenic climate change. Until climate models and impact models become better integrated, it is necessary to rely heavily on multistep attribution, in which hydrological changes are shown to result from climatic changes that may in turn result partly from human activities.

Extreme hydrological events, such as floods, prompt speculation about whether they are "caused" by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also—because of the need for model simulations—uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold magnitude. Call this fraction r_{ctrl} in the simulated actual climate and r_{expt} in the simulated climate in which there is no anthropogenic forcing, and suppose there are many paired instances of r_{ctrl} and r_{expt}, with the ratio of risks in each pair given by $F = r_{expt} / r_{ctrl}$. The distribution of risk ratios F describes the likelihood that the climate change has altered the risk. Several thousand pairs of such simulations were run to estimate the risk ratio for the floods in England and Wales in autumn 2000 (Pall et al., 2011). Each pair started from a unique initial state that differed slightly from a common reference state, and was obtained with a seasonal forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century. The forecast model was coupled to a model of basin-scale runoff and channel-scale hydraulics. It is not probable that such exercises will become routine for assessing single-event risks in, for example, the insurance industry, because the necessary amount of computation is so formidable. Nevertheless, the result was compelling: in each of the four sets of simulation pairs, the risk increased greatly on average in the runs forced by anthropogenic greenhouse radiation. In aggregate, the most probable amount of increase was two- to threefold, and at most a few percent of the simulation pairs suggested that anthropogenic forcing actually decreased the risk. This summary is worded carefully: the thousands of simulation pairs were needed for quantifying the uncertainties, which led unavoidably to a spread of likelihoods and thus to statements about uncertainty about risk that are themselves uncertain.

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901–2005 are statistically insignificant (Bates et al., 2008; WGI AR5 Chapter 2). According to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt et al., 2010), and certain trends in total and extreme precipitation amounts are observed (WGI AR5 Chapter 2). Most regional changes in precipitation are attributed either to internal variability of the atmospheric circulation or to global warming (Lambert et al., 2004; Stott et al., 2010). It was estimated that the 20th century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation (Zhang et al., 2007). Changes in snowfall amounts are indeterminate, as for precipitation; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier (Takala et al., 2009). In Norway, increased temperature at lower altitudes has reduced the snow water equivalent (Skaugen et al., 2012).

Steady decreases since the 1960s of global and regional actual evapotranspiration and pan evaporation have been attributed to changes in precipitation, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor pressure deficit, and wind speed (Fu et al., 2009; McVicar et al., 2010; Miralles et al., 2011; Wang A. et al., 2011). Regional downward and upward trends in soil moisture content have been calculated for China from 1950 to 2006, where longer, more severe, and more frequent soil moisture droughts have been experienced over 37% of the land area (Wang A. et al., 2011). This is supported by detected increases since the 1960s in dry days and a prolongation of dry periods (Gemmer et al., 2011; Fischer et al., 2013), and can be attributed to increases in warm days and warm periods (Fischer et al., 2011).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example, in some regions of the Arctic and Eurasia (WGI AR5 Chapter 4) and the Andes (Rabassa, 2009). Active layer depth and permafrost degradation are closely dependent on soil ice content. In steep terrain, slope stability is highly affected by changes in permafrost (Harris et al., 2009). The release of greenhouse gases (GHGs) due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not yet well represented in global climate models (Grosse et al., 2011). In most parts of the world glaciers are losing mass (Gardner et al., 2013). For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s (Rabassa, 2009; Rabatel et al., 2013); similarly, Himalayan glaciers are losing mass at present (Bolch et al., 2012).

3.2.3. Streamflow

Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow (1962–2004) decreased in the south and east and generally increased elsewhere (Stahl et al., 2010, 2012), particularly in northern latitudes (Wilson et al., 2010). In North America (1951–2002), increases were observed in the Mississippi basin and decreases in the U.S. Pacific Northwest and southern Atlantic–Gulf regions (Kalra et al., 2008). In China, a decrease in streamflow in the Yellow River (1960–2000) is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze River shows a small increase in annual streamflow driven by an increase in monsoon rains (Piao et al., 2010; see Table 3-1). These and other streamflow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land use changes (Zhang and Schilling, 2006), irrigation (Kustu et al., 2010), and urbanization (Wang and Cai, 2010).

In a global analysis of simulated streamflows (1948–2004), about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai et al., 2009). Decreasing trends in low and mid-latitudes are consistent with recent drying and warming in West Africa, southern Europe, south and east Asia, eastern Australia, western Canada and the USA, and northern South America (Dai, 2013). The contribution to observed streamflow changes due to decreased stomatal opening of many plant species at higher carbon dioxide (CO_2) concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*robust evidence*, *high agreement*) and has increased winter flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan et al., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham et al., 2008; Smith, 2000). Where streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (Cayan et al., 2001; Knowles et al., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult owing to additional influences of land use changes and groundwater abstractions (Stoll et al., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare owing to a lack of appropriate observation wells and a small number of studies. Observed decreases of the discharge of groundwater-fed springs in Kashmir (India) since the 1980s were attributed to observed precipitation decreases (Jeelani, 2008; Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge not only decreased strongly during the 20th century due to the decreasing precipitation but also that groundwater recharge as a fraction of observed precipitation declined progressively, possibly indicating an increase in evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

3.2.5. Water Quality

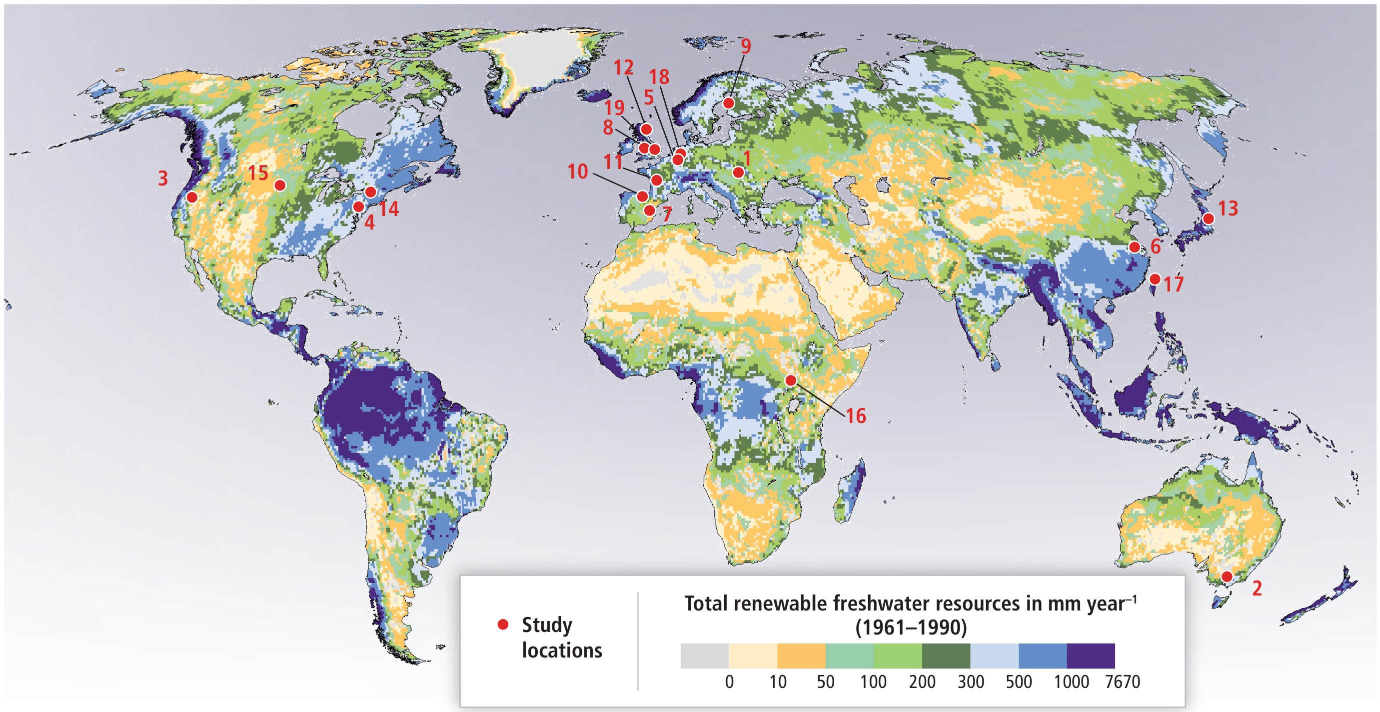
Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short term. For lakes and reservoirs, the most frequently reported change is more intense eutrophication and algal blooms at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*medium* to *robust evidence*, *high agreement*). Increased runoff results in greater loads of salts, fecal coliforms, pathogens, and heavy metals (Pednekar et al., 2005; Paerl et al., 2006; Tibby and Tiller, 2007; Boxall et al., 2009) (*robust evidence*, *medium* to *high agreement*, depending on the pollutant). In some cases there are associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by 10% when turbidity increased in the raw water of a drinking water plant even when treated using conventional procedures (Schwartz et al., 2000). However, positive impacts were also reported. For example, the risk of eutrophication was reduced when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl and Huisman, 2008). For rivers, all reported impacts on water quality were negative. Greater runoff, instead of diluting pollution, swept more pollutants from the soil into watercourses (*robust evidence*, *medium* to *high agreement*) (Boxall et al., 2009; Loos et al., 2009; Benítez-Gilabert et al., 2010; Gascuel-Odoux et al., 2010; Howden et al., 2010; Saarinen et al., 2010; Tetzlaff et al., 2010; Macleod et al., 2012). Increased organic matter content impaired the quality of conventionally treated drinking water (Weatherhead and Howden, 2009). In streams in semiarid and arid areas, temperature changes had a stronger influence on the increase of organic matter, nitrates, and phosphorus than precipitation changes (Ozaki et al., 2003; Chang, 2004; Benítez-Gilabert et al., 2010) (*limited evidence*, *medium agreement*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of fecal coliforms during the rainy season or after extreme rain events (*medium evidence*, *high agreement*), with varying response times (Curriero et al., 2001; Tumwine et al., 2002, 2003; Auld et al., 2004; Jean et al., 2006; Seidu et al., 2013). Given the widespread use of groundwater for municipal supply and minimal or lacking treatment of drinking water in poor regions, increased pollution is a source of concern (Jean et al., 2006; Seidu et al., 2013). Another concern is the nonlinearity (except for temperature) of relationships between water quality and climatic variables (*limited evidence*, *medium agreement*). In general, the linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime, and the many other possible sources of pollution (*high confidence*; Senhorst and Zwolsman, 2005; Whitehead et al., 2009a; Benítez-Gilabert et al., 2010; Howden et al., 2010; Kundzewicz and Krysanova, 2010; Ventela et al., 2011).

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne et al., 2012), which suggests an increase in rainfall erosivity that would enhance soil erosion and stream sediment loads. A warmer climate may affect soil moisture, litter cover, and biomass production and can bring about a shift in winter precipitation from snow to more erosive rainfall (Kundzewicz et al., 2007) or, in semiarid regions, an increase in wildfires with subsequent rainfall leading to intense erosive events (Nyman et al., 2011; Bussi et al., 2013). The effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities (Walling, 2009).

Only few studies have isolated the contribution of climate change to observed trends in soil erosion and sediment load. In the Yellow River basin, where soil erosion results mostly from heavy rainfall, reduced precipitation (~10%) contributed about 30% to a total reduction in stream sediment loads reaching the sea during 2000–2005, compared to 1950–1968, with the remaining 70% attributable to sediment trapping in reservoirs and soil conservation measures (Wang et al., 2007; Miao et al., 2011). Dai et al. (2008), analyzing the decrease in sediment load of the Yangtze River over 1956–2002, found that climate change was responsible for an increase of about 3 ± 2%; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.

3



	Location	Study period	Observation on water quality	Reference
1	Danube River, Bratislava, Slovakia	1926–2005	The water temperature is rising but the trend of the weighted long-term average temperature values resulted close to zero because of the interannual distribution of the mean monthly discharge.	Pekarova et al. (2008)
2	Purrumbete, Colac and Bullen Merri Lakes, Victoria, Australia	1984–2000	The increases in salinity and nutrient content were associated with the air temperature increase; salinity in addition was associated with variations in the effective precipitation.	Tibby and Tiller (2007)
3	Lake Tahoe, California and Nevada States, USA	1970–2007	Thermal stability resulting from a higher ambient temperature decreased the dissolved oxygen content.	Sahoo et al. (2010)
4	Neuse River Estuary, North Carolina, USA	1979–2003	Intense storms and hurricanes flushed nutrients from the estuary, reducing eutrophic conditions and the risk of algal blooms.	Paerl et al., (2006); Paerl and Huisman (2008)
5	River Meuse, western Europe	1976–2003	Increase of water temperature and the content of major elements and some heavy metals were associated with droughts. Algal blooms resulted from a higher nutrient content due to higher water temperature and longer residence time.	van Vliet and Zwolsman (2008)
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake, already suffering from periodic cyanobacterial blooms, was affected by a very intensive bloom in May 2007 attributed to an unusually warm spring and leading to the presence of *Microcystis* toxins in the water. This forced two million people to drink bottled water for at least one week.	Qin et al. (2010)
7	Sau Reservoir, Spain	1964–2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen.	Marcé et al. (2010)
8	22 upland waters in UK	1988–2002	Dissolved organic matter increased due to temperature increase but also due to rainfall variations, acid deposition, land use, and CO_2 enrichment.	Evans et al. (2005)
9	Coastal rivers from western Finland	1913–2007	Low pH values are associated with higher rainfall and river discharge in an acid sulfate soil basin.	Saarinen et al. (2010)
		1961–2007	Critical values of dissolved organic carbon is associated with higher rainfall and river discharge.	
10	15 pristine mountain rivers, northern Spain	1973–2005	For a semiarid area, there is a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilabert et al. (2010)
11	30 coastal rivers and groundwater of western France	1973–2007 (2–6 years)	Interannual variations in the nutrient content associated with air temperature, rainfall, and management practices changes. These effects were not observed in groundwater because of the delay in response time and the depuration of soil on water.	Gascuel-Odoux et al. (2010)
12	Girnock, Scotland	14 months	Higher risks of fecal pollution are clearly related to rainfall during the wet period.	Tetzlaff et al. (2010)
13	27 rivers in Japan	1987–1995	Increases in organic matter and sediment and decreases in the dissolved oxygen content are associated with increases in ambient temperature. Precipitation increases and variations are associated with an increase in the organic matter, sediments, and chemical oxygen demand content in water.	Ozaki et al. (2003)
14	Conestoga River Basin, Pennsylvania, USA	1977–1997	There is a close association between annual loads of total nitrogen and annual precipitation increases.	Chang (2004)
15	USA	1948–1994	Increased rainfall and runoff are associated with site-specific outbreaks of waterborne disease.	Curriero et al. (2001)
16	Northern and eastern Uganda	1999–2001, 2004, 2007	Elevated concentrations of fecal coliforms are observed in groundwater-fed water supplies during the rainy season.	Tumwine et al. (2002, 2003); Taylor et al. (2009)
17	Taiwan, China	1998	The probability of detecting cases of enterovirus infection was greater than 50%, with rainfall rates >31 mm h^{-1}. The higher the rainfall rate, the higher the probability of an enterovirus epidemic.	Jean et al. (2006)
18	Rhine Basin	1980–2001	Nutrient content in rivers followed seasonal variations in precipitation which were also linked to erosion within the basin.	Loos et al. (2009)
19	River Thames, England	1868–2008	Higher nutrient contents were associated to changes in river runoff and land use.	Howden et al. (2010)

Figure 3-2 | Observations of the impacts of climate on water quality.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with pronounced glacier retreat (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive for a global diagnosis of sediment load changes; there are both decreasing (e.g., Iceland; Lawler et al., 2003) and increasing trends (Patagonia; Fernandez et al., 2011). So far, there is no clear evidence that the frequency or magnitude of shallow landslides has changed over past decades (Huggel et al., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker et al., 2009). Increased landslide impacts (measured by casualties or losses) in south and Southeast Asia, where landslides are triggered predominantly by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *limited evidence* and *low agreement* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads, and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the impacts of land use and land cover changes are more significant than those of climate change.

3.2.7. Extreme Hydrological Events and their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale (Kundzewicz et al., 2013). The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Moreover, in the attribution of detected changes it is difficult to distinguish the roles of climate and human activities (Section 3.2.1). However, recent detection of trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). More locations show increases in heavy precipitation than decreases (Seneviratne et al., 2012). Flood damage costs worldwide have been increasing since the 1970s, although this is partly due to increasing exposure of people and assets (Handmer et al., 2012).

There is no strong evidence for trends in observed flooding in the USA (Hirsch and Ryberg, 2012), Europe (Mudelsee et al., 2003; Stahl et al., 2010; Benito and Machado, 2012; Hannaford and Hall, 2012), South America, and Africa (Conway et al., 2009). However, at smaller spatial scales, an increase in annual maximum discharge has been detected in parts of northwestern Europe (Petrow and Merz, 2009; Giuntoli et al., 2012; Hattermann et al., 2012), while a decrease was observed in southern France (Giuntoli et al., 2012). Flood discharges in the lower Yangtze basin increased over the last 40 years (Jiang et al., 2008; Zhang et al., 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani et al., 2008). In Australia, only 30% of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak et al., 2010). In Arctic rivers dominated by a snowmelt regime, there is no general trend in flood magnitude and frequency (Shiklomanov et al., 2007). In Nordic countries, significant changes since the mid-20th century are mostly toward earlier seasonal flood peaks, but flood magnitudes show contrasting trends, driven by temperature and precipitation, in basins with and without glaciers increasing peaks in the former and decreasing peaks in the latter (Wilson et al., 2010; Dahlke et al., 2012). Significant trends at almost one-fifth of 160 stations in Canada were reported, most of them decreases in snowmelt-flood magnitudes (Cunderlik and Ouarda, 2009). Similar decreases were found for spring and annual maximum flows (Burn et al., 2010).

Attribution has been addressed by Hattermann et al. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explainable in terms of increasing frequency and persistence of circulation patterns favorable to flooding (Petrow et al., 2009). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min et al., 2011; see also Section 3.2.1).

Socioeconomic losses from flooding are increasing (*high confidence*), although attribution to anthropogenic climate change is established only seldom (Pall et al., 2011). Reported flood damages (adjusted for inflation) have increased from an average of US$7 billion per year in the 1980s to about US$24 billion per year in 2011 (Kundzewicz et al., 2013). Economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product are higher in developing countries. Since 1970, the annual number of flood-related deaths has been in the thousands, with more than 95% in developing countries (Handmer et al., 2012). There is *high confidence* (*medium evidence*, *high agreement*) that greater exposure of people and assets, and societal factors related to population and economic growth, contributed to the increased losses (Handmer et al., 2012; Kundzewicz et al., 2013). When damage records are normalized for changes in exposure and vulnerability (Bouwer, 2011), most studies find no contribution of flooding trends to the trend in losses (Barredo, 2009; Hilker et al., 2009; Benito and Machado, 2012), although there are exceptions (Jiang et al., 2005; Chang et al., 2009).

Assessments of observed changes in "drought" depend on the definition of drought (meteorological, agricultural, or hydrological) and the chosen drought index (e.g., consecutive dry days, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Runoff Index (SRI); see Seneviratne et al., 2012). Meteorological (rainfall) and agricultural (soil moisture) droughts have become more frequent since 1950 (Seneviratne et al., 2012) in some regions, including southern Europe and western Africa, but in others (including the southern USA; Chen et al., 2012) there is no evidence of change in frequency (WGI AR5 Chapter 2).

Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions. A trend was found toward lower summer minimum flows for 1962–2004 in small catchments in southern and Eastern Europe, but there was no clear trend in northern or Western Europe (Stahl et al., 2010). Models can reproduce observed patterns of drought occurrence (e.g., Prudhomme et al., 2011), but as with climate models their outputs can be very divergent. In simulations of drought at the global scale in 1963–2000 with an ensemble of hydrological models, strong correlations were noted between El Niño-

Southern Oscillation (ENSO) events and hydrological droughts, and—particularly in dry regions—low correlations between meteorological and hydrological droughts, which suggests that hydrological droughts cannot necessarily be inferred from rainfall deficits (van Huijgevoort et al., 2013).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to atmospheric water vapor content, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. Temperature has increased in recent decades while surface and tropospheric relative humidity have changed little (WGI AR5 Chapter 2). Among other climatic drivers are atmospheric CO_2, which affects plant transpiration (Box CC-VW), and deposited black carbon and dust, both of which, even in very small concentrations, enhance melting of snow and ice by reducing the surface albedo.

Uncertainty in the climatic drivers is due mainly to internal variability of the atmospheric system, inaccurate modeling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in Coupled Model Intercomparison Project Phase 3 (CMIP3) projections (Hawkins and Sutton, 2011). The contribution of internal variability diminishes progressively. By no later than mid-century, most of the uncertainty in precipitation is due to discrepancies between models, and divergent scenarios never contribute more than one-third of the uncertainty. In contrast, the uncertainty in temperature (WGI AR5 Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI AR5 Chapter 12), with further constraints added here from 20th century observations, can be summarized as follows:

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases non-uniformly (*very high confidence*), probably by about 1.5 times more over land than over ocean.
- Warming is greatest over the Arctic (*very high confidence*), implying latitudinally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and snow cover decreases in extent and duration (*high confidence*). In the coldest regions, however, increased winter snowfall outweighs increased summer snowmelt.
- Wet regions and seasons become wetter and dry regions and seasons become drier (*high confidence*), although one observational analysis (Sun et al., 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake et al., 2012) and its observed sensitivity to temperature (Liu et al., 2012).
- Global mean precipitation increases in a warmer world (*virtually certain*), but with substantial variations, including some decreases, from region to region. Precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and Central America, and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia (*likely* to *very likely*; WGI AR5 Figure 12-41). However, precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions projected 21st century changes lie within the range of late 20th century natural variability (Mahlstein et al., 2012).
- Changes in evaporation have patterns similar to those of changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes (WGI AR5 Figure 12-25). Scenario-dependent decreases of soil moisture are widespread, particularly in central and southern Europe, southwestern North America, Amazonia, and southern Africa (*medium* to *high confidence*; WGI AR5 Figure 12-23; WGI AR5 Section 12.4.5.3).

More intense extreme precipitation events are expected (IPCC, 2012). One proposed reason is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to "empty" the water vapor from the atmospheric column (Utsumi et al., 2011; Berg et al., 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986–2005 are projected to have shorter return periods in 2081–2100: about 14 years for RCP2.6, 11 years for RCP4.5, and 6 years for RCP8.5 (Kharin et al., 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5 to 2.5% K^{-1}, the 20-year return amount of daily precipitation typically increases at 4 to 10% K^{-1}. Agreement between model-simulated extremes and reanalysis extremes is good in the extratropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10 ± 4% K^{-1}, O'Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between models is the dominant contributor to uncertainty. Model-simulated changes in the incidence of meteorological (rainfall) droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne et al., 2012). Regions where droughts are projected to become longer and more frequent include the Mediterranean, central Europe, central North America, and southern Africa.

3.3.2. Non-Climatic Drivers

In addition to impacts of climate change, the future of freshwater systems will be impacted strongly by demographic, socioeconomic, and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socioeconomic futures can produce similar climate changes (van Vuuren et al., 2012), meaning that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic, and ecological conditions. Similarly, the same future socioeconomic conditions can be associated with a range of different climate futures.

Changing land use is expected to affect freshwater systems strongly in the future. For example, increasing urbanization may increase flood hazards and decrease groundwater recharge. Of particular importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009).

Owing mainly to population and economic growth but also to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase owing to increased variability of surface water supply caused by climate change (Taylor R. et al., 2013a).

3.4. Projected Hydrological Changes

3.4.1. Methodological Developments in Hydrological Impact Assessment

Most recent studies of the potential impact of climate change on hydrological characteristics have used a small number of climate scenarios. An increasing number has used larger ensembles of regional or global models (e.g., Chiew et al., 2009; Gosling et al., 2010; Arnell, 2011; Bae et al., 2011; Jackson et al., 2011; Olsson et al., 2011; Kling et al., 2012; Arnell and Gosling, 2013). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009b; Manning et al., 2009; Christierson et al., 2012; Liu et al., 2013). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered. Very few impact studies (Dankers et al., 2013; Hanasaki et al., 2013; Portmann et al., 2013; Schewe et al., 2013) have so far used scenarios based on CMIP5 climate models, and these have used only a small subset.

Most assessments have used a hydrological model with the "delta method" to create scenarios, which applies projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. Several approaches to the construction of scenarios at the catchment scale have been developed (Fowler et al., 2007), including dynamical downscaling using regional climate models and a variety of statistical approaches (e.g., Fu et al., 2013). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data, and the range in projected change between downscaling approaches can be as large as the range between different climate models (Quintana Segui et al., 2010; Chen J. et al., 2011). An increasing number of studies (e.g., Fowler and Kilsby, 2007; Hagemann et al., 2011; Kling et al., 2012; Teutschbein and Seibert, 2012; Veijalainen et al., 2012; Weiland et al., 2012a) have run hydrological models with bias-corrected input from regional or global climate model output (van Pelt et al., 2009; Piani et al., 2010; Yang et al., 2010), rather than by applying changes to an observed baseline. The range between different bias correction methods can be as large as the range between climate models (Hagemann et al., 2011), although this is not always the case (Chen C. et al., 2011; Muerth et al., 2013). Some studies (e.g., Falloon and Betts, 2006, 2010; Hirabayashi et al., 2008; Nakaegawa et al., 2013) have examined changes in global-scale river runoff as simulated directly by a high-resolution climate model, rather than by an "off-line" hydrological model. Assessments of the ability of climate models directly to simulate current river flow regimes (Falloon et al., 2011; Weiland et al., 2012b) show that performance depends largely on simulated precipitation and is better for large basins, but the *limited evidence* suggests that direct estimates of change are smaller than off-line estimates (Hagemann et al., 2013).

The effects of hydrological model parameter uncertainty on simulated runoff changes are typically small when compared with the range from a large number of climate scenarios (Steele-Dunne et al., 2008; Cloke et al., 2010; Vaze et al., 2010; Arnell, 2011; Lawrence and Haddeland, 2011). However, the effects of hydrological model structural uncertainty on projected changes can be substantial (Dankers et al., 2013; Hagemann et al., 2013; Schewe et al., 2013), owing to differences in the representation of evaporation and snowmelt processes. In some regions (e.g., high latitudes; Hagemann et al., 2013) with reductions in precipitation (Schewe et al., 2013), hydrological model uncertainty can be greater than climate model uncertainty—although this is based on small numbers of climate models. Much of the difference in projected changes in evaporation is due to the use of different empirical formulations (Milly and Dunne, 2011). In a study in southeast Australia, the effects of hydrological model uncertainty were small compared with climate model uncertainty, but all the hydrological models used the same potential evaporation data (Teng et al., 2012).

Among other approaches to impact assessment, an inverse technique (Cunderlik and Simonovic, 2007) starts by identifying the hydrological changes that would be critical for a system and then uses a hydrological model to determine the meteorological conditions that trigger those changes; the future likelihood of these conditions is estimated by inspecting climate model output, as in a catchment study in Turkey (Fujihara et al., 2008a,b). Another approach constructs response surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterize the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue et al., 2011; Renner and Bernhofer, 2012; Renner et al., 2012). A response surface showing change in flood magnitudes was constructed by running a hydrological model with systematically varying changes in climate (Prudhomme et al., 2010). This approach shows the sensitivity of a system to change, and also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration, Soil Moisture, and Permafrost

Based on global and regional climate models as well as physical principles, potential evapotranspiration over most land areas is *very likely* to increase in a warmer climate, thereby accelerating the hydrologic cycle (WGI AR5 Chapter 12). Long-term projections of actual evapotranspiration are uncertain in both magnitude and sign. They are affected not only by rising temperatures but also by changing net radiation and soil moisture, decreases in bulk canopy conductance associated with rising CO_2 concentrations, and vegetation changes related to climate change (Box CC-VW; Katul and Novick, 2009). Projections of the response of potential evapotranspiration to a warming climate are also uncertain. Based on six different methodologies, an increase in potential evapotranspiration was associated with global warming (Kingston et al., 2009). Regionally, increases are projected in southern Europe, Central America, southern Africa, and Siberia (Seneviratne et al., 2010). The accompanying decrease in soil moisture increases the

Box 3-1 | Case Study: Himalayan Glaciers

The total freshwater resource in the Himalayan glaciers of Bhutan, China, India, Nepal, and Pakistan is known only roughly; estimates range from 2100 to 5800 Gt (Bolch et al., 2012). Their mass budgets have been negative on average for the past 5 decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere. A recent large-scale measurement, highlighted in Figure 3-3, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

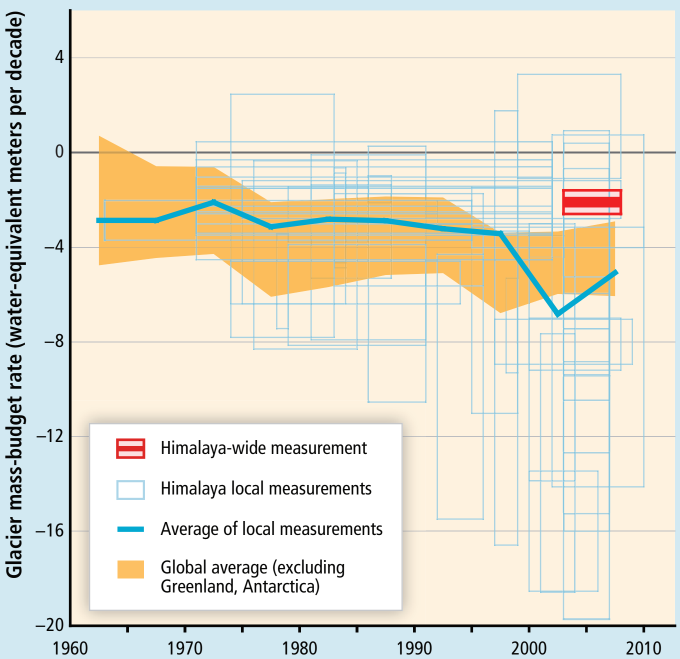


Figure 3-3 | All published glacier mass balance measurements from the Himalaya (based on Bolch et al., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multiannual measurements). Region-wide measurement (Kääb et al., 2012) was by satellite laser altimetry. Global average (WGI AR5 Chapter 4) is shown as a 1-sigma confidence region.

Glacier mass changes for 2006–2100 were projected by simulating the response of a glacier model to CMIP5 projections from 14 General Circulation Models (GCMs) (Radić et al., 2013). Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15 to 78% under RCP4.5. The model-mean loss to 2100 is 45% under RCP4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier erroneous assessment (Cruz et al., 2007) of complete disappearance by 2035.

At the catchment scale, projections do not yet present a detailed region-wide picture. However the GCM-forced simulations of Immerzeel et al. (2013) in Kashmir and eastern Nepal show runoff increasing throughout the century. Peak ice meltwater is reached in mid- to late-century, but increased precipitation overcompensates for the loss of ice.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal by Yasunari et al. (2010) suggest that this could yield 70 to 200 mm yr^{-1} of additional meltwater. Deposited soot may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian et al., 2011).

The hazard due to moraine-dammed ice-marginal lakes continues to increase. In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle et al., 2011). There has been little progress on the predictability of dam failure but, of five dams that have failed since 1980, all had frontal slopes steeper than 10° before failure and much gentler slopes afterward (Fujita et al., 2013). This is a promising tool for evaluating the hazard in detail.

The relative importance of Himalayan glacier meltwater decreases downstream, being greatest where the runoff enters dry regions in the west and becoming negligible in the monsoon-dominated east (Kaser et al., 2010). In the mountains, however, dependence on and vulnerability to glacier meltwater are of serious concern when measured per head of population.

risk of extreme hot days (Seneviratne et al., 2006; Hirschi et al., 2011) and heat waves. For a range of scenarios, soil moisture droughts lasting 4 to 6 months double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century (Sheffield and Wood, 2008). Because of strong natural variability, the generally monotonic projected increases are statistically indistinguishable from the current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost of northern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (WGI AR5 Figure 4-18). Under RCP2.6, the permafrost area is projected to stabilize at near 37% less than the 20th century area.

3.4.3. Glaciers

All projections for the 21st century (WGI AR5 Chapter 13) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts toward spring (e.g., Huss, 2011). This shift is expected with *very high confidence* in most regions, although not, for example, in the eastern Himalaya, where the monsoon and the melt season coincide. The relative importance of high-summer glacier meltwater can be substantial, for example contributing 25% of August discharge in basins draining the European Alps, with area about 105 km^2 and only 1% glacier cover (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig et al., 2007).

If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum: "peak meltwater." Peak-meltwater dates have been projected between 2010 and 2050 (parts of China, Xie et al., 2006); 2010–2040 (European Alps, Huss, 2011); and mid- to late-century (glaciers in Norway and Iceland, Jóhannesson et al., 2012). Note that the peak can be dated only relative to a specified reference date. Declining yields relative to various dates in the past have been detected in some observational studies (Table 3-1); that is, a peak has been passed already. There is *medium confidence* that the peak response to 20th- and 21st-century warming will fall within the 21st century in many inhabited glacierized basins, where at present society is benefitting from a transitory "meltwater dividend." Variable forcing leads to complex variations of both the melting rate and the extent of ice, which depend on each other.

If they are in equilibrium, glaciers reduce the interannual variability of water resources by storing water during cold or wet years and releasing it during warm years (Viviroli et al., 2011). As glaciers shrink, however, their diminishing influence may make the water supply less dependable.

3.4.4. Runoff and Streamflow

Many of the spatial gaps identified in AR4 have been filled to a very large extent by catchment-scale studies of the potential impacts of climate change on streamflow. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature, and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation: the smaller the ratio, the greater the sensitivity. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier, 2012).

Projected scenario-dependent changes in runoff at the global scale, mostly from CMIP3 simulations, exhibit a number of consistent patterns (e.g., Hirabayashi et al., 2008; Döll and Zhang, 2010; Fung et al., 2011; Murray et al., 2012; Okazaki et al., 2012; Tang and Lettenmaier, 2012; Weiland et al., 2012a; Arnell and Gosling, 2013; Nakaegawa et al., 2013; Schewe et al., 2013). Average annual runoff is projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. However, for some regions there is very considerable uncertainty in the magnitude and direction of change, specifically in China, south Asia, and large parts of South America. Both the patterns of change and the uncertainty are driven largely by projected changes in precipitation, particularly across south Asia. Figure 3-4 shows the average percentage change in average annual runoff for an increase in global average temperature of 2°C above the 1980–2010 mean, averaged across five CMIP5 climate models and 11 hydrological models. The pattern of change in Figure 3-4 is different in some regions from the pattern shown in WGI AR5 Figure 12-24, largely because it is based on fewer climate models.

The seasonal distribution of change in streamflow varies primarily with the seasonal distribution of change in precipitation, which in turn varies between scenarios. Figure 3-5 illustrates this variability, showing the percentage change in monthly average runoff in a set of catchments from different regions using scenarios from seven climate models, all scaled to represent a 2°C increase in global mean temperature above the 1961–1990 mean. One of the climate models is separately highlighted, and for that model the figure also shows changes with a 4°C rise in temperature. In the Mitano catchment in Uganda, for example, there is a nonlinear relationship between amount of climate change and hydrological response. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

There is a much more consistent pattern of future seasonal change in areas currently influenced by snowfall and snowmelt. A global analysis (Adam et al., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some regions where increases in precipitation are sufficient to result in increased, rather than decreased, snow accumulation during winter. The greatest changes are found near the boundaries of regions that currently experience considerable snowfall, where the marginal effect of higher temperatures on snowfall and snowmelt is greatest.

3.4.5. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of studies and review papers

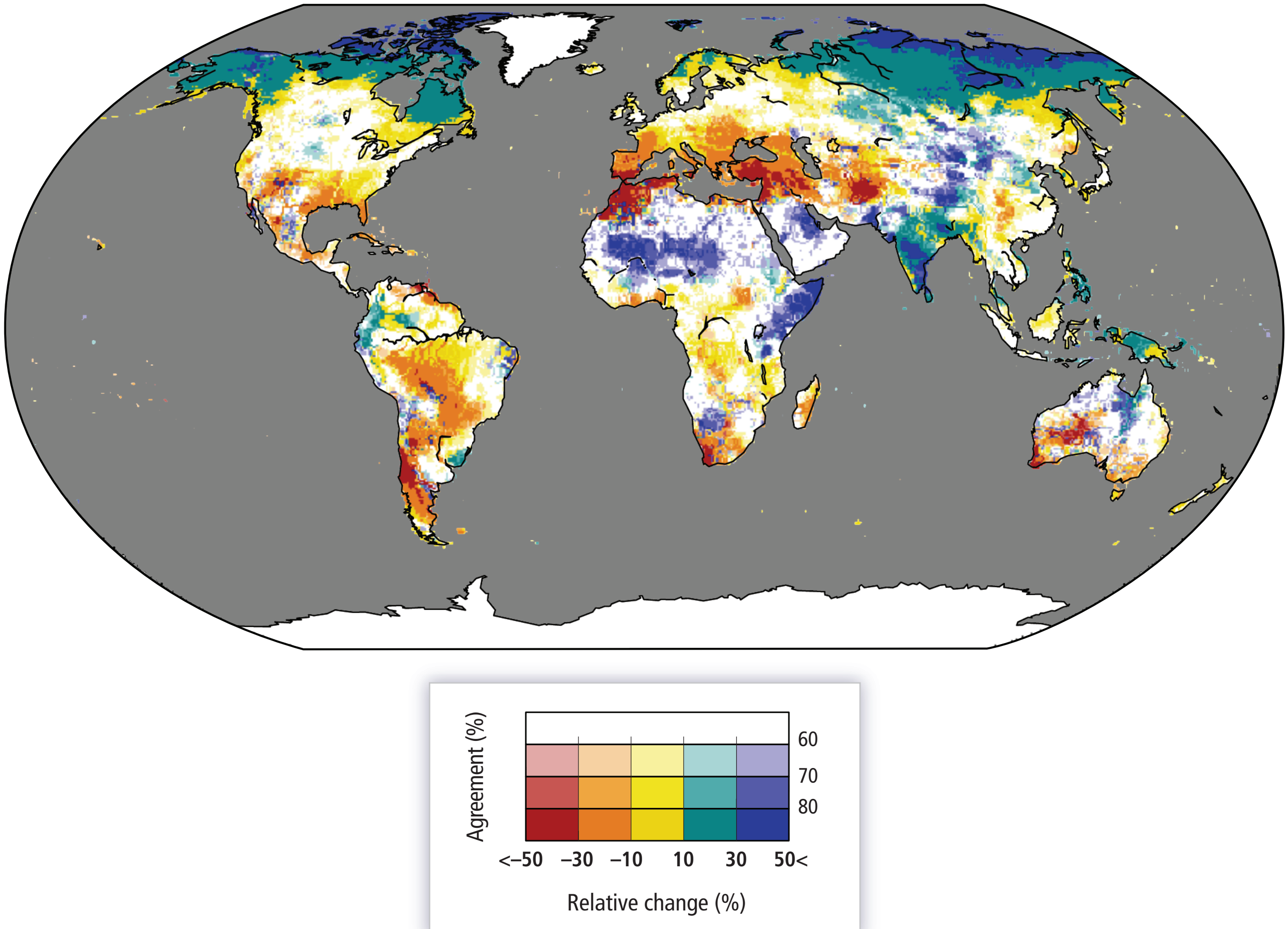


Figure 3-4 | Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe et al., 2013).

(Green et al., 2011; Taylor R. et al., 2013a) has increased significantly since then. Ensemble studies, relying on between 4 and 20 climate models, of the impact of climate change on groundwater recharge and partially also on groundwater levels were done for the globe (Portmann et al., 2013), all of Australia (Crosbie et al., 2013a), the German Danube basin (Barthel et al., 2010), aquifers in Belgium and England (Goderniaux et al., 2011; Jackson et al., 2011), the Pacific coast of the USA and Canada (Allen et al., 2010), and the semiarid High Plains aquifer of the USA (Ng et al., 2010; Crosbie et al., 2013b). With three exceptions, simulations were run under only one GHG emissions scenario. The range over the climate models of projected groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percentage changes of projected groundwater recharge mostly exceeded the range of projected precipitation changes. The uncertainties in projected groundwater recharge that originate in the hydrological models have not yet been explored. There are only a few studies of the impacts on groundwater of vegetation changes in response to climate change and CO_2 increase (Box CC-VW). Nor are there any studies on the impact of climate-driven changes of land use on groundwater recharge, even though projected increases in precipitation and streamflow variability due to climate change are expected to lead to increased groundwater abstraction (Taylor R. et al., 2013a), lowering groundwater levels and storage.

Under any particular climate scenario, the areas where total runoff (sum of surface runoff and groundwater recharge) is projected to increase (or decrease) roughly coincide with the areas where groundwater recharge and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect the fraction of total runoff that recharges groundwater. Increased precipitation intensity may decrease groundwater recharge owing to exceedance of the infiltration capacity (typically in humid areas), or may increase it owing to faster percolation through the root zone and thus reduced evapotranspiration (typically in semiarid areas) (Liu, 2011; Taylor R. et al., 2013b). The sensitivity of groundwater recharge and levels to climate change is diminished by perennial vegetation, fine-grained soils, and aquitards and is enhanced by annual cropping, sandy soils, and unconfined (water table) aquifers (van Roosmalen et al., 2007; Crosbie et al., 2013b). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater

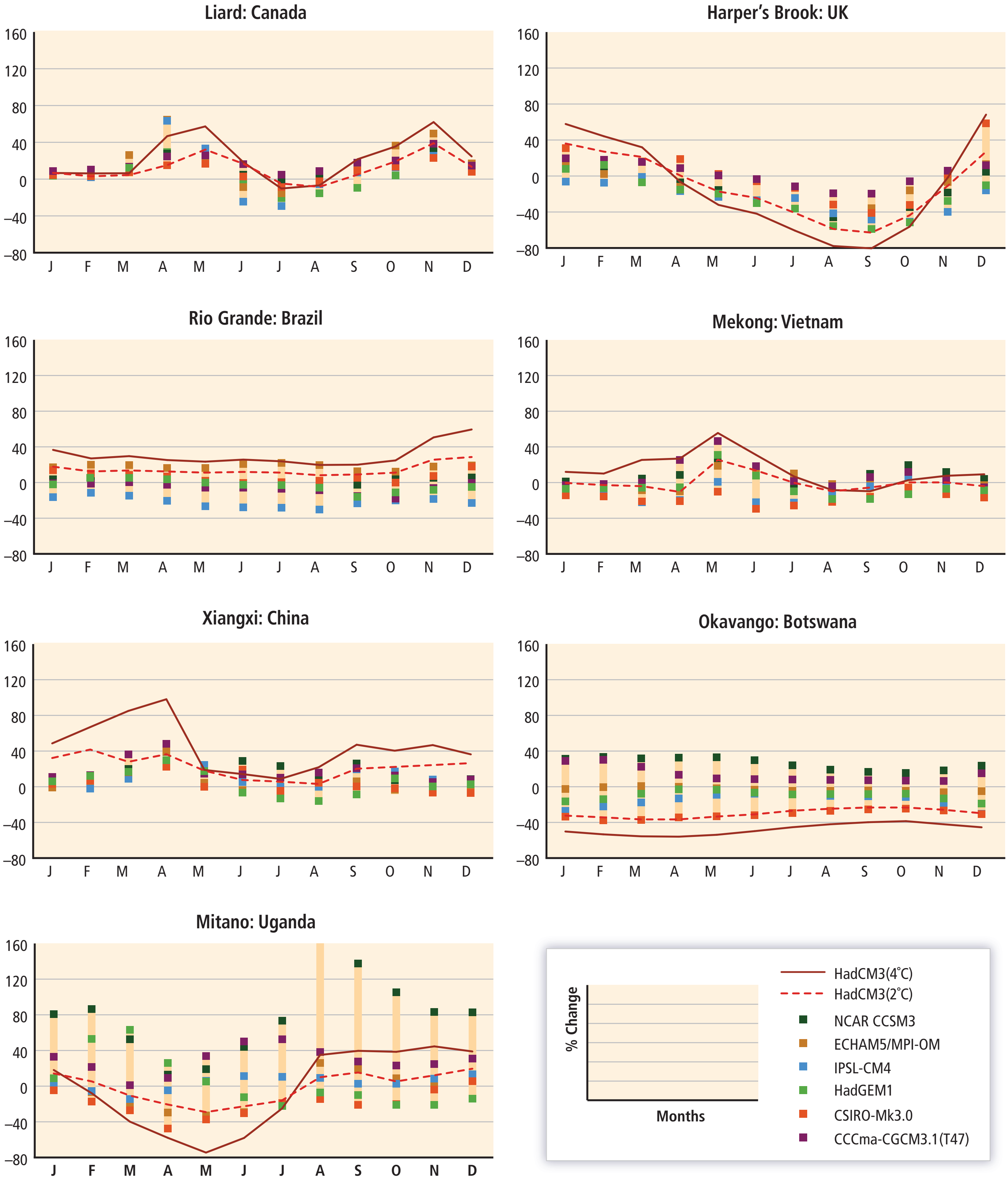


Figure 3-5 | Change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature above 1961–1990 (Kingston and Taylor, 2010; Arnell, 2011; Hughes et al., 2011; Kingston et al., 2011; Nobrega et al., 2011; Thorne, 2011; Xu et al., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2°C increase (dotted line) and a 4°C increase (solid line).

recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semiarid High Plains aquifer (Crosbie et al., 2013b). Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the southwestern USA, snowmelt provides at least 40 to 70% of groundwater recharge, although only 25 to 50% of average annual precipitation falls as snow (Earman et al., 2006).

Climate change affects coastal groundwater not only through changes in groundwater recharge but also through sea level rise which, together with the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. Although most confined aquifers are expected to be unaffected by sea level rise, unconfined aquifers are expected to suffer from saltwater intrusion (Werner et al., 2012). The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises (Masterson and Garabedian, 2007; Werner et al., 2012). This happens where land surfaces are low lying, for example, on many coral islands and in deltas, but also where groundwater discharges to streams. If the difference between the groundwater table and sea level is decreased by 1 m, the thickness of the unconfined freshwater layer decreases by roughly 40 m (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive saltwater into stream channels, contaminating the underlying fresh groundwater from above (Masterson and Garabedian, 2007). In three modeling studies, the impact of sea level rise on groundwater levels was found to be restricted to areas within 10 km from the coast (Carneiro et al., 2010; Oude Essink et al., 2010; Yechieli et al., 2010). Saltwater intrusion due to sea level rise is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011). Even small rates of groundwater pumping from coastal aquifers are expected to lead to stronger salinization of the groundwater than sea level rise during the 21st century (Ferguson and Gleeson, 2012; Loaiciga et al., 2012).

Changes in groundwater recharge also affect streamflow. In the Mitano basin in Uganda, mean global temperature increases of 4°C or more with respect to 1961–1990 are projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010; Figure 3-5). Changing groundwater tables affect land surface energy fluxes, including evaporation, and thus feed back on the climate system, in particular in semiarid areas where the groundwater table is within 2 to 10 m of the surface (Jiang et al., 2009; Ferguson and Maxwell, 2010).

3.4.6. Water Quality

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series. Projections under climate change scenarios are difficult, both to perform and interpret, because they require not only integration of the climate models with those used to analyze the transportation and transformation of pollutants in water, soil, and air but also the establishment of a proper baseline (Arheimer et al., 2005; Andersen et al., 2006; Wilby et al., 2006; Ducharne, 2008; Marshall and Randhir, 2008; Bonte and Zwolsman, 2010; Towler et al., 2010; Trolle et al., 2011; Rehana and Mujumdar, 2012). The models have different spatial scales and have to be adapted and calibrated to local conditions for which adequate and appropriate information is needed. In consequence, there are few projections of the impacts of climate change on water quality; where available, their uncertainty is high. It is evident, however, that water quality projections depend strongly on (1) local conditions; (2) climatic and environmental assumptions; and (3) the current or reference pollution state (Chang, 2004; Whitehead et al., 2009a,b; Bonte and Zwolsman, 2010; Kundzewicz and Krysanova, 2010; Sahoo et al., 2010; Trolle et al., 2011). Most projections suggest that future negative impacts will be similar in kind to those already observed in response to change and variability in air and water temperature, precipitation, and storm runoff, and to many confounding anthropogenic factors (Chang, 2004; Whitehead et al., 2009a). This holds for natural and artificial reservoirs (Brikowski, 2008; Ducharne, 2008; Marshall and Randhir, 2008; Loos et al., 2009; Bonte and Zwolsman, 2010; Qin et al., 2010; Sahoo et al., 2010; Trolle et al., 2011), rivers (Andersen et al., 2006; Whitehead et al., 2009a,b; Bowes et al., 2012) and groundwater (Butscher and Huggenberger, 2009; Rozemeijer et al., 2009).

3.4.7. Soil Erosion and Sediment Load

Heavy rainfalls are *likely* to become more intense and frequent during the 21st century in many parts of the world (Seneviratne et al., 2012; WGI AR5 Chapter 11), which may lead to more intense soil erosion even if the total rainfall does not increase. At the global scale, soil erosion simulated assuming doubled CO_2 is projected to increase about 14% by the 2090s, compared to the 1980s (9% attributed to climate change and 5% to land use change), with increases by as much as 40 to 50% in Australia and Africa (Yang et al., 2003). The largest increases are expected in semiarid areas, where extreme events may contribute about half of total erosion; for instance, in Mediterranean Spain 43% of sediment yield over the time period 1990–2009 was produced by a single event (Bussi et al., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex nonlinear ways; for instance in the UK a 10% increase in winter rainfall (i.e., during early growing season) could increase annual erosion of arable land by up to 150% (Favis-Mortlock and Boardman, 1995), while in Austria a simulation for 2070–2099 projected a decrease of rainfall by 10 to 14% in erosion-sensitive months and thus a decline in soil erosion by 11 to 24% (Scholz et al., 2008). Land management practices are critical for mitigating soil erosion under projected climate change. In China's Loess Plateau, four GCMs coupled to an erosion model show soil erosion increasing by –5 to 195% of soil loss during 2010–2039 under conventional tillage, for three emission scenarios (*Special Report on Emission Scenarios* (SRES) A2 and B2, and IS92a), whereas under conservation tillage they show decreases of 26 to 77% (Li et al., 2011).

Climate change will also affect the sediment load in rivers by altering water discharge and land cover. For example, an increase in water discharge of 11 to 14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9 to 36% during 2071–2100 (Thodsen et al., 2008). Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions (Lu et al., 2010). In a major

Frequently Asked Questions

FAQ 3.1 | How will climate change affect the frequency and severity of floods and droughts?

Climate change is projected to alter the frequency and magnitude of both floods and droughts. The impact is expected to vary from region to region. The few available studies suggest that flood hazards will increase over more than half of the globe, in particular in central and eastern Siberia, parts of Southeast Asia including India, tropical Africa, and northern South America, but decreases are projected in parts of northern and Eastern Europe, Anatolia, central and East Asia, central North America, and southern South America (*limited evidence*, *high agreement*).The frequency of floods in small river basins is *very likely* to increase, but that may not be true of larger watersheds because intense rain is usually confined to more limited areas. Spring snowmelt floods are *likely* to become smaller, both because less winter precipitation will fall as snow and because more snow will melt during thaws over the course of the entire winter. Worldwide, the damage from floods will increase because more people and more assets will be in harm's way.

By the end of the 21st century meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels. Droughts are projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa. In dry regions, more intense droughts will stress water supply systems. In wetter regions, more intense seasonal droughts can be managed by current water supply systems and by adaptation; for example, demand can be reduced by using water more efficiently, or supply can be increased by increasing the storage capacity in reservoirs.

headwater basin of the Ganges River, increased precipitation and glacier runoff are projected to increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropics, the intensity of cyclones is projected to increase 2 to 11% by 2100, which may increase soil erosion and landslides (Knutson et al., 2010).

In summary, projected increases in heavy rainfall and temperature will lead to changes in soil erosion and sediment load, but owing to the nonlinear dependence of soil erosion on rainfall rate and its strong dependence on land cover there is *low confidence* in projected changes in erosion rates. At the end of the 21st century, the impact of climate change on soil erosion is expected to be twice the impact of land use change (Yang et al., 2003), although management practices may mitigate the problem at catchment scale.

3.4.8. Extreme Hydrological Events (Floods and Droughts)

The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; Seneviratne et al., 2012) recognized that projected increases in temperature and heavy precipitation imply regional-scale changes in flood frequency and intensity, but with *low confidence* because these projections were obtained from a single GCM. Global flood projections based on multiple CMIP5 GCM simulations coupled with global hydrology and land surface models (Dankers et al., 2013; Hirabayashi et al., 2013) show flood hazards increasing over about half of the globe, but with great variability at the catchment scale. Projections of increased flood hazard are consistent for parts of south and Southeast Asia, tropical Africa, northeast Eurasia, and South America (Figure 3-6), while decreases are projected in parts of northern and Eastern Europe, Anatolia, central Asia, central North America, and southern South America. This spatial pattern resembles closely that described by Seneviratne et al. (2012), but the latest projections justify *medium confidence* despite new appreciation of the large uncertainty owing to variation between climate models and their coupling to hydrological models.

There have been several assessments of the potential effect of climate change on meteorological droughts (less rainfall) and agricultural droughts (drier soil) (e.g., WGI AR5 Chapter 12; Vidal et al., 2012; Orlowsky and Seneviratne, 2013), but few on hydrological droughts, either in terms of river runoff or groundwater levels. Many catchment-scale studies (Section 3.4.4) consider changes in indicators of low river flow (such as the flow exceeded 95% of the time), but these indicators do not necessarily characterize "drought" as they define neither duration nor spatial extent, and are not necessarily particularly extreme or rare. In an ensemble comparison under SRES A1B of the proportion of the land surface exhibiting significant projected changes in hydrological drought frequency to the proportions exhibiting significant changes in meteorological and agricultural drought frequency, 18 to 30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, while about 15 to 45% saw a decrease (Taylor I. et al., 2013). This is a smaller area with increased frequency, and a larger area with decreased frequency, than for meteorological and agricultural droughts, and is understandable because river flows reflect the accumulation of rainfall over time. Flows during dry periods may be sustained by earlier rainfall. For example, at the catchment scale in the Pacific Northwest (Jung and Chang, 2012),

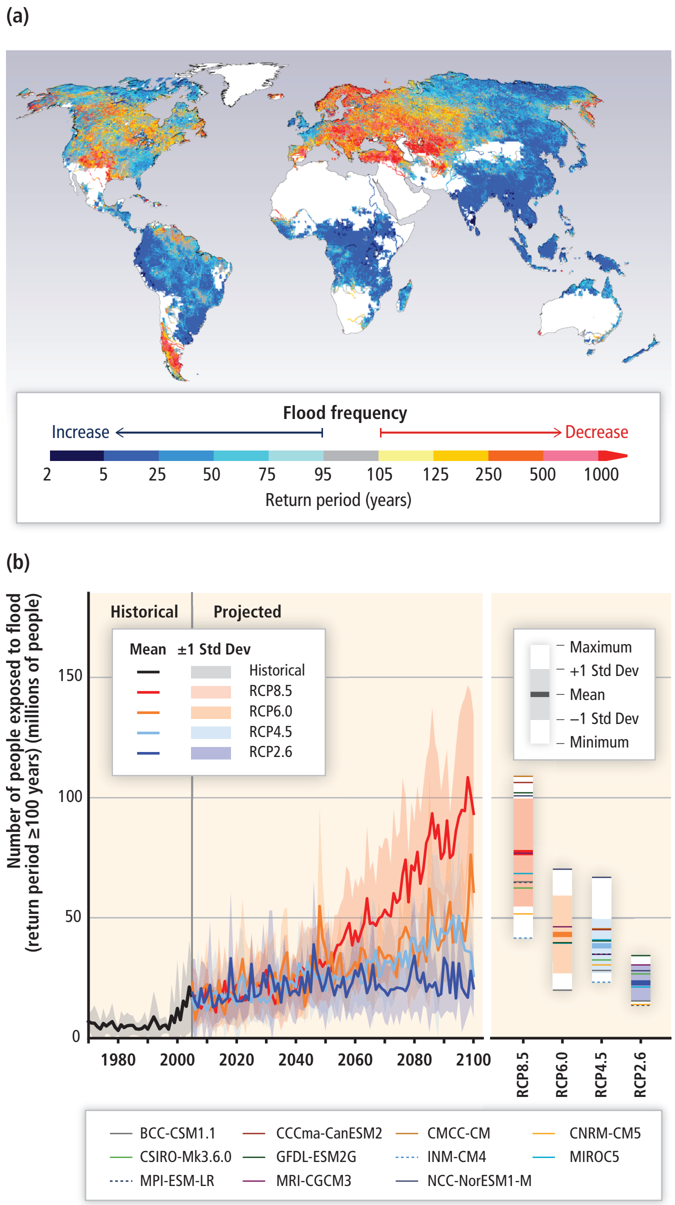


Figure 3-6 | (a) Multi-model median return period (years) in the 2080s for the 20th century 100-year flood (Hirabayashi et al., 2013), based on one hydrological model driven by 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) under Representative Concentration Pathway 8.5 (RCP8.5). At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. Regions with mean runoff less than 0.01 mm day^{-1}, Antarctica, Greenland, and Small Islands are excluded from the analysis and indicated in white. (b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi et al., 2013). Left: Ensemble means of historical (black thick line) and future simulations (colored thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: Maximum and minimum (extent of white), mean (thick colored lines), ±1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) averaged over the 21st century. The impact of 21st century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4 to 14 times as compared to the 20th century (4 ± 3 (RCP2.6), 7 ± 5 (RCP4.5), 7 ± 6 (RCP6.0), and 14 ± 10 (RCP8.5) times, or 0.1% to 0.4 to 1.2% of the global population in 2005). Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7 to 25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.

short hydrological droughts are projected to increase in frequency while longer droughts remain unchanged because, although dry spells last longer, winter rainfall increases.

The impacts of floods and droughts are projected to increase even when the hazard remains constant, owing to increased exposure and vulnerability (Kundzewicz et al., 2013). Projected flood damages vary greatly between models and from region to region, with the largest losses in Asia. Studies of projected flood damages are mainly focused in Europe, the USA, and Australia (Handmer et al., 2012; Bouwer, 2013). In Europe, the annual damage (€6.4 billion) and number of people exposed (200,000) in 1961–1990 are expected to increase about twofold by the 2080s under scenario B2 and about three times under scenario A2 (Feyen et al., 2012). Drought impacts at continental and smaller scales are difficult to assess because they will vary greatly with the local hydrological setting and water management practices (Handmer et al., 2012). More frequent droughts due to climate change may challenge existing water management systems (Kim et al., 2009); together with an increase of population, this may place at risk even the domestic supply in parts of Africa (MacDonald et al., 2009).

3.5. Projected Impacts, Vulnerabilities, and Risks

In general, projections of freshwater-related impacts, vulnerabilities, and risks caused by climate change are evaluated by comparison to historical conditions. Such projections are helpful for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare the different hydrological changes that are projected under different future GHG emissions scenarios, or different amounts of global mean temperature rise. One objective of such projections is to quantify what may happen under current water resources management practice, and another is to indicate what actions may be needed to avoid undesirable outcomes (Oki and Kanae, 2006). The studies compiled in Table 3-2 illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems. Emissions scenarios are rather similar until the 2050s. Their impacts, and thus the benefits of mitigation, tend to become more clearly marked by the end of the 21st century. For example, the fraction of the world population exposed to a 20th century 100-year flood is projected to be, at the end of the 21st century, three times higher per year for RCP8.5 than for RCP2.6 (Hirabayashi et al., 2013). Each degree of global warming (up to 2.7°C above preindustrial levels; Schewe et al., 2013) is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population. The number of people with significantly decreased access to renewable groundwater resources is projected to be roughly 50% higher under RCP8.5 than under RCP2.6 (Portmann et al., 2013). The percentage of global population living in river basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2°C to 13% at 5°C (Gerten et al., 2013).

3.5.1. Availability of Water Resources

About 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability,

Table 3-2 | Effects of different greenhouse gas (GHG) emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the Special Report on Emission Scenarios (SRES) scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. Representative Concentration Pathway 8.5 (RCP8.5) is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the Coupled Model Intercomparison Project Phase 5 (CMIP5) model mean) over different reference periods, typically since pre-industrial. GW since pre-industrial is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2090s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2090s, while in RCP2.6, GW stays below 1.5°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase. The number of GCMs that were used in the studies is provided.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 General Circulation Models (GCMs) and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C), each degree of GW affects an additional 7%	Schewe et al. (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	• RCP2.6: 24% (11–39%) • RCP4.5: 26% (23–32%) • RCP6.0: 32% (18–45%) • RCP8.5: 38% (27–50%)	Portmann et al. (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5–11 GCMs, population constant at 2005 values)	• RCP2.6: 0.4% (0.2–0.5%) • RCP4.5: 0.6% (0.4–1.0%) • RCP6.0: 0.7% (0.3–1.1%) • RCP8.5: 1.2% (0.6–1.7%) • GW 2°C: 0.5% (0.3–0.6%) • GW 4°C: 1.2% (0.8–2.2%) • 1980s: 0.1% (0.04–0.16%)	Hirabayashi et al. (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	• RCP2.6: –0.2 to 1.6% • RCP4.5: 1.9–2.8% • RCP8.5: 6.7–10.0%	Hanasaki et al. (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	• SRES B2: 5.4–6.7% • SRES A2: 6.3–7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 m^3 yr^{-1} of per capita blue water resources in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten et al. (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 m^3 yr^{-1} of per capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	• GW 2°C: 8% • GW 3.5°C: 11% • GW 5°C: 13%	Gerten et al. (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 m^3 yr^{-1} of per capita blue water resources) exposed to an increase in stress (1 GCM)	For emissions scenarios with 2°C target, compared to SRES A1: • 5–8% impact reduction in 2050 • 10–20% reduction in 2100	Arnell et al. (2013)
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	• GW 1.4°C: close to 0 almost everywhere • GW 2.8°C: in western Australia 0.2–0.6, in central Australia 0.2–0.3, elsewhere close to 1	Crosbie et al. (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	• SRES B1: –22% • SRES A1f: –26%	Holman et al. (2009)
Change of river discharge, groundwater recharge, and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario.	van Roosmalen et al. (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW.	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area, and magnitude of short and long drought events throughout the 21st century (1 GCM)	Smaller increases over time for SRES B1 than for A2 and A1B.	Vidal et al. (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg L^{-1}) (2) Maximum duration of MAC exceedance (2050, 1 GCM)	• Reference period 1997–2007 (GW 0.8°C): (1) 2.5%, (2) 103 days • GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days • GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950–99 (11 GCMs)	• SRES B1: 8% • SRES A2: 7%	Beyene et al. (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031–2060, 3 GCMs)	• Without climate change: 16 • SRES B1: 22 • SRES A2: 24	van Vliet et al. (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006 (2) Expected annual population exposed (2080s, 2 GCMs)	• SRES B2: (1) 14–15 billion € yr^{-1}, (2) 440,000–470,000 people • SRES A2: (1) 18–21 billion € yr^{-1}, (2) 510,000–590,000 people • Reference period: (1) 6.4 billion € yr^{-1}, (2) 200,000 people	Feyen et al. (2012)

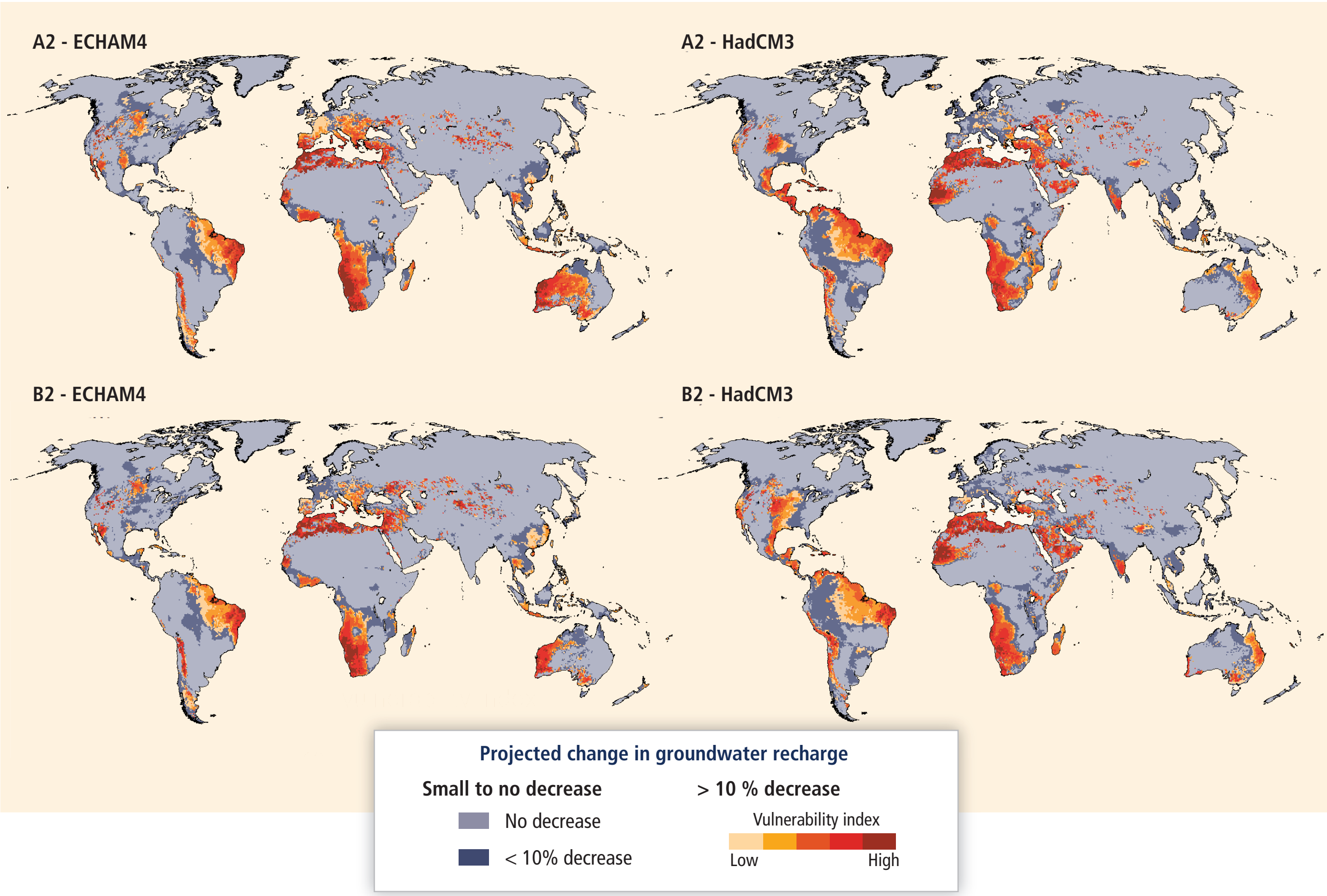


Figure 3-7 | Human vulnerability to climate change–induced decreases of renewable groundwater resources by the 2050s. Lower (Special Report on Emission Scenarios (SRES) B2) and higher (SRES A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is defined only for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961–1990 (Döll, 2009).

water demand, and pollution (Vörösmarty et al., 2010). Climate change can alter the availability of water and therefore threaten water security as defined by UNESCO (2011).

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vörösmarty et al. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Hayashi et al., 2010; Arnell et al., 2011, 2013; Fung et al., 2011; Murray et al., 2012; Gerten et al., 2013; Gosling and Arnell, 2013; Schewe et al., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to availability from runoff or recharge (Arnell et al., 2011; Gosling and Arnell, 2013; Hanasaki et al., 2013). A groundwater vulnerability index was constructed that combined future reductions of renewable groundwater resources with water scarcity, dependence on groundwater, and the Human Development Index (Figure 3-7) (Döll, 2009). There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably between climate models, and strongly with the pattern of projected rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and East Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.4), and therefore less exposure to water resources stress. Third, over the next few decades and for increases in global mean temperature of less than around 2°C above preindustrial, changes in population will generally have a greater effect on changes in resource availability than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures. Fourth, estimates of future water availability are sensitive not only to climate and population projections and population assumptions, but also to the choice of hydrological impact model (Schewe et al., 2013) and to the adopted measure of stress or scarcity. As an indication of the potential magnitude of the impact of climate change, Schewe et al. (2013) estimated that about 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1°C rise in global mean temperature (compared to the 1990s), rising to 14% at 2°C and 17% at 3°C; the spread across climate and hydrological models was, however, large.

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to

Frequently Asked Questions

FAQ 3.2 | How will the availability of water resources be affected by climate change?

Climate models project decreases of renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions (*high agreement*, *robust evidence*). Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality; for instance, the quality of lakes used for water supply could be impaired by the presence of algae-producing toxins.

increased precipitation variability and decreased snow and ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is sustainable only where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Therefore, groundwater cannot be expected to ease freshwater stress where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources of more than 10% between the 1980s and the 2080s was computed to range from 24% (mean based on five GCMs, range 11 to 39%) for RCP2.6 to 38% (range 27 to 50%) for RCP8.5 (Portmann et al., 2013; see also Table 3-2). The land area affected by decreases of groundwater resources increases linearly with global mean temperature rise between 0°C and 3°C. For each degree of global mean temperature rise, an additional 4% of the global land area is projected to suffer a groundwater resources decrease of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann et al., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Water demand and use for food and livestock feed production is governed not only by crop management and its efficiency, but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rainfed systems. Using projections from 19 CMIP3 GCMs forced by SRES A2 emissions to drive a global vegetation and hydrology model, climate change by the 2080s would hardly alter the global irrigation water demand of major crops in areas currently equipped for irrigation (Konzmann et al., 2013). However, there is *high confidence* that irrigation demand will increase significantly in many areas (by more than 40% across Europe, USA, and parts of Asia). Other regions—including major irrigated areas in India, Pakistan, and southeastern China—might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios (also see Biemans et al., 2013). Using seven global hydrological models but a limited set of CMIP5 projections, Wada et al. (2013) suggested a global increase in irrigation demand by the 2080s (ensemble average 7 to 21% depending on emissions scenario), with a pronounced regional pattern, a large inter-model spread, and possible seasonal shifts in crop water demand and consumption. By contrast, based on projections from two GCMs and two emissions scenarios, a slight global decrease in crop water deficits was suggested in both irrigated and rainfed areas by the 2080s, which can be explained partly by a smaller difference between daily maximum and minimum temperatures (Zhang and Cai, 2013). As in other studies, region-to-region variations were very heterogeneous.

Where poor soil is not a limiting factor, physiological and structural crop responses to elevated atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann et al., 2013; see also Box CC-VW). However, even in this optimistic case, increases in irrigation water demand by >20% are still projected under most scenarios for some regions, such as southern Europe. In general, future irrigation demand is projected to exceed local water availability in many places (Wada et al., 2013). The water demand to produce a given amount of food on either irrigated or rainfed cropland will increase in many regions due to climate change alone (Gerten et al., 2011, projections from 17 CMIP3 GCMs, SRES A2 emissions), but this increase might be moderated by concurrent increases in crop water productivity due to CO_2 effects, that is, decreases in per-calorie water demand. The CO_2 effects may thus lessen the global number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is *likely* to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten et al., 2011).

Rainfed agriculture is vulnerable to increasing precipitation variability. Differences in yield and yield variability between rainfed and irrigated land may increase with changes in climate and its variability (e.g., Finger et al., 2011). Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter (Yoo et al., 2013). Water demand for rainfed crops could be reduced by better management (Brauman et al., 2013), but unmitigated climate change may counteract such efforts, as shown in a global modeling study (Rost et al., 2009). In some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013).

3.5.2.2. Energy Production

Hydroelectric and thermal power plants, and the irrigation of bioenergy crops (Box CC-WE), require large amounts of water. This section assesses the impact of hydrological changes (as described in Section 3.4) on hydroelectric and thermal power production. The impacts of changes in energy production due to climate change mitigation efforts are discussed in Section 3.7.2.1, while the economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are assessed in Chapter 10.

Climate change affects hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows, and increases of streamflow variability (including floods and droughts), as well as by increased evaporation from reservoirs and changes in sediment fluxes. Therefore, the impact of climate change on a specific hydropower plant will depend on the local change of these hydrological characteristics, as well as on the type of hydropower plant and on the (seasonal) energy demand, which will itself be affected by climate change (Golombek et al., 2012). Run-of-river power plants are more susceptible to increased flow variability than plants at dams. Projections of future hydropower generation are subject to the uncertainty of projected precipitation and streamflow. For example, projections to the 2080s of hydropower generation in the Pacific Northwest of the USA range from a decrease of 25% to an increase of 10% depending on the climate model (Markoff and Cullen, 2008). Based on an ensemble of 11 GCMs, hydropower generation at the Aswan High Dam (Egypt) was computed to remain constant until the 2050s but to decrease, following the downward trend of mean annual river discharge, to 90% (ensemble mean) of current mean annual production under both SRES B1 and A2 (Beyene et al., 2010; see also Table 3-2). In snow-dominated basins, increased discharge in winter, smaller and earlier spring floods, and reduced discharge in summer have already been observed (Section 3.2.6) and there is *high confidence* that these trends will continue. In regions with high electricity demands for heating, this makes the annual hydrograph more similar to seasonal variations in electricity demand, reducing required reservoir capacities and providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt et al., 2010; Golombek et al., 2012). In regions with high electricity demand for summertime cooling, however, this seasonal streamflow shift is detrimental. In general, climate change requires adaptation of operating rules (Minville et al., 2009; Raje and Mujumdar, 2010) which may, however, be constrained by reservoir capacity. In California, for example, high-elevation hydropower systems with little storage, which rely on storage in the snowpack, are projected to yield less hydropower owing to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, owing to increases in stream temperatures and the incidence of low flows (Flörke et al., 2012; van Vliet et al., 2012; see also Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5 to 3% in European countries by the 2080s under emissions scenario SRES A1B (Golombek et al., 2012).

3.5.2.3. Municipal Services

Under climate change, water utilities are confronted by the following (Bates et al., 2008; Jiménez, 2008; van Vliet and Zwolsman, 2008; Black and King, 2009; Brooks et al., 2009; Whitehead et al., 2009a; Bonte and Zwolsman, 2010; Hall and Murphy, 2010; Mukhopadhyay and Dutta, 2010; Qin et al., 2010; Chakraborti et al., 2011; Major et al., 2011; Thorne and Fenner, 2011; Christierson et al., 2012):

- Higher ambient temperatures, which reduce snow and ice volumes and increase the evaporation rate from lakes, reservoirs, and aquifers. These changes decrease natural storage of water, and hence, unless precipitation increases, its availability. Moreover, higher ambient temperatures increase water demand, and with it the competition for the resource (*medium* to *high agreement*, *limited evidence*).
- Shifts in timing of river flows and possible more frequent or intense droughts, which increase the need for artificial water storage.
- Higher water temperatures, which encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water (*high agreement*, *medium evidence*). On the positive side, biological water and wastewater treatment is more efficient when the water is warmer (Tchobanoglous et al., 2003).
- Possibly drier conditions, which increase pollutant concentrations. This is a concern especially for groundwater sources that are already of low quality, even when pollution is natural as in India and Bangladesh, North and Latin America and Africa; here arsenic, iron, manganese, and fluorides are often a problem (Black and King, 2009).
- Increased storm runoff, which increases loads of pathogens, nutrients, and suspended sediment.
- Sea level rise, which increases the salinity of coastal aquifers, in particular where groundwater recharge is also expected to decrease.

Climate change also impacts water quality indirectly. For instance, at present many cities rely on water from forested catchments that requires very little treatment. More frequent and severe forest wildfires could seriously degrade water quality (Emelko et al., 2011; Smith et al., 2011).

Many drinking water treatment plants—especially small ones—are not designed to handle the more extreme influent variations that are to be expected under climate change. These demand additional or even different infrastructure capable of operating for up to several months per year, which renders wastewater treatment very costly, notably in rural areas (Zwolsman et al., 2010; Arnell et al., 2011).

Sanitation technologies vary in their resilience to climate impacts (Howard et al., 2010). For sewage, three climatic conditions are of interest (NACWA, 2009; Zwolsman et al., 2010):

- Wet weather: heavier rainstorms mean increased amounts of water and wastewater in combined systems for short periods. Current

designs, based on critical "design storms" defined through analysis of historical precipitation data, therefore need to be modified. New strategies to adapt to and mitigate urban floods need to be developed, considering not only climate change but also urban design, land use, the "heat island effect," and topography (Changnon, 1969).
- Dry weather: soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to infiltration and exfiltration of water and wastewater. The combined effects of higher temperatures, increased pollutant concentrations, longer retention times, and sedimentation of solids may lead to increasing corrosion of sewers, shorter asset lifetimes, more drinking water pollution, and higher maintenance costs.
- Sea level rise: intrusion of brackish or salty water into sewers necessitates processes that can handle saltier wastewater.

Increased storm runoff implies the need to treat additional wastewater when combined sewers are used, as storm runoff adds to sewage; in addition, the resulting mixture has a higher content of pathogens and pollutants. Under drier conditions higher concentrations of pollutants in wastewater, of any type, are to be expected and must be dealt with (Whitehead et al., 2009a,b; Zwolsman et al., 2010). The cost may rule this out in low-income regions (Chakraborti et al., 2011; Jiménez, 2011). The disposal of wastewater or fecal sludge is a concern that is just beginning to be addressed in the literature (Seidu et al., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are composed of biota (animals, plants, and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs, or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. They have suffered more strongly from human activities than have marine and terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millennium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems, which it affects not only through increased water temperatures (discussed in Section 4.3.3.3) but also by altered streamflow regimes, river water levels, and extent and timing of inundation (Box CC-RF). Wetlands in dry environments are hotspots of biological diversity and productivity, and their biotas are at risk of extinction if runoff decreases and the wetland dries out (as described for Mediterranean-type temporary ponds by Zacharias and Zamparas, 2010). Freshwater ecosystems are also affected by water quality changes induced by climate change (Section 3.2.5), and by human adaptations to climate change-induced increases of streamflow variability and flood risk, such as the construction of dykes and dams (Ficke et al., 2007; see also Section 3.7.2).

3.5.2.5. Other Uses

In addition to direct impacts, vulnerabilities, and risks in water-related sectors, indirect impacts of hydrological changes are expected for navigation, transportation, tourism, and urban planning (Pinter et al., 2006; Koetse and Rietveld, 2009; Rabassa, 2009; Badjeck et al., 2010; Beniston, 2012). Social and political problems can result from hydrological changes. For example, water scarcity and water overexploitation may increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Burke et al. 2009; Buhaug et al., 2010; Hsiang et al., 2011). Snowline rise and glacier shrinkage are *very likely* to impact environmental, hydrological, geomorphological, heritage, and tourism resources in cold regions (Rabassa, 2009), as already observed for tourism in the European Alps (Beniston, 2012). Although most impacts will be adverse, some might be beneficial.

3.6. Adaptation and Managing Risks

In the face of hydrological changes and freshwater-related impacts, vulnerability, and risks due to climate change, there is need for adaptation and for increasing resilience. Managing the changing risks due to the impacts of climate change is the key to adaptation in the water sector (IPCC, 2012), and risk management should be part of decision making and the treatment of uncertainty (ISO, 2009). Even to exploit the positive impacts of climate change on freshwater systems, adaptation is generally required.

Frequently Asked Questions

FAQ 3.3 | How should water management be modified in the face of climate change?

Managers of water utilities and water resources have considerable experience in adapting their policies and practices to the weather. But in the face of climate change, long-term planning (over several decades) is needed for a future that is highly uncertain. A flexible portfolio of solutions that produces benefits regardless of the impacts of climate change ("low-regret" solutions) and that can be implemented adaptively, step by step, is valuable because it allows policies to evolve progressively, thus building on—rather than losing the value of—previous investments. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water reuse, desalination, and more efficient soil and irrigation water management. Restoring and protecting freshwater habitats, and managing natural floodplains, are additional adaptive measures that are not usually part of conventional management practice.

3.6.1. Options

There is growing agreement that an adaptive approach to water management can successfully address uncertainty due to climate change. Although there is *limited evidence* of the effectiveness of such an approach, the evidence is growing (Section 3.6.2). Many practices identified as adaptive were originally reactions to climate variability. Climate change provides many opportunities for "low-regret" solutions, capable of yielding social and/or economic benefits and adaptive both to variability and to change (Table 3-3). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. A program of adaptation typically mixes "hard" infrastructural and "soft" institutional measures (Bates et al., 2008; Cooley, 2008; Mertz et al., 2009; Sadoff and Muller, 2009; UNECE, 2009; Olhoff and Schaer, 2010).

To avoid adaptation that goes wrong—"maladaptation"—scientific research results should be analyzed during planning. Low-regret solutions, such as those for which moderate investment clearly increases the capacity to cope with projected risks or for which the investment is justifiable under all or almost all plausible scenarios, should be considered explicitly. Involving all stakeholders, reshaping planning processes, coordinating the management of land and water resources, recognizing linkages between water quantity and quality, using surface water and groundwater conjunctively, and protecting and restoring natural systems are examples of principles that can beneficially inform planning for adaptation (World Bank, 2007).

Integrated Water Resource Management continues to be a promising instrument for exploring adaptation to climate change. It can be joined with a Strategic Environmental Assessment to address broader considerations. Attention is currently increasing to "robust measures" (European Communities, 2009), which are measures that perform well under different future conditions and clearly optimize prevailing strategies (Sigel et al., 2010). Barriers to adaptation are discussed in detail in Section 16.4. Barriers to adaptation in the freshwater sector include lack of human and institutional capacity, lack of financial resources, lack of awareness, and lack of communication (Browning-Aiken et al., 2007; Burton, 2008; Butscher and Huggenberger, 2009; Zwolsman et al., 2010). Institutional structures can be major barriers to adaptation (Goulden et al., 2009; Engle and Lemos, 2010; Huntjens et al., 2010; Stuart-Hill and Schulze, 2010; Ziervogel et al., 2010; Wilby and Vaughan, 2011; Bergsma et al., 2012); structures that promote participation of and collaboration between stakeholders tend to encourage adaptation. Some adaptation measures may not pass the test of workability in an uncertain future (Campbell et al., 2008), and uncertainty (Section 3.6.2) can be another significant barrier.

Case studies of the potential effectiveness of adaptation measures are increasing. Changes in operating practices and infrastructure improvements could help California's water managers respond to changes in the volume and timing of supply (Medellin-Azuara et al., 2008; Connell-Buck et al., 2011). Other studies include evaluations of the effectiveness of different adaptation options in Washington state, USA (Miles et al., 2010) and the Murray-Darling basin, Australia (Pittock and Finlayson, 2011), and of two dike-heightening strategies in the Netherlands (Hoekstra and de Kok, 2008). Such studies have demonstrated that it is technically feasible in general to adapt to projected climate changes, but not all have considered how adaptation would be implemented.

3.6.2. Dealing with Uncertainty in Future Climate Change

One of the key challenges in factoring climate change into water resources management lies in the uncertainty. Some approaches (e.g., in England and Wales; Arnell, 2011) use a small set of climate scenarios to characterize the potential range of impacts on water resources and flooding. Others (e.g., Brekke et al., 2008; Lopez et al., 2009; Christierson et al., 2012; Hall et al., 2012) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Hall, 2007; Stainforth et al., 2007; Dessai et al., 2009) that attempts to construct probability distributions of impacts are misguided because of "deep" uncertainty, which arises because analysts do not know, or cannot agree on, how the climate system and water management systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth et al. (2007) therefore argue that it is impossible in practice to construct robust quantitative probability distributions of climate change impacts, and that climate change uncertainty needs to be represented differently, for example by using fewer plausible scenarios and interpreting the outcomes of scenarios less quantitatively.

Some go further, arguing that climate models are not sufficiently robust or reliable to provide the basis for adaptation (Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010; Blöschl and Montanari, 2010; Wilby, 2010), because they are frequently biased and do not reproduce the temporal characteristics (specifically the persistence or "memory") often found in hydrological records. It has been argued (Lins and Cohn, 2011; Stakhiv, 2011) that existing water resources planning methods are sufficiently robust to address the effects of climate change. This view of climate model performance has been challenged and is the subject of some debate (Koutsoyiannis et al., 2009, 2011; Huard, 2011); the critique also assumes that adaptation assessment procedures would use only climate scenarios derived directly from climate model simulations.

Addressing uncertainty in practice by quantifying it through some form of risk assessment, however, is only one way of dealing with uncertainty. A large and increasing literature recommends that water managers should move from the traditional "predict and provide" approach toward adaptive water management (Pahl-Wostl, 2007; Pahl-Wostl et al., 2008; Matthews and Wickel, 2009; Mysiak et al., 2009; Huntjens et al., 2012; Short et al., 2012; Gersonius et al., 2013) and the adoption of resilient or "no-regrets" approaches (WWAP, 2009; Henriques and Spraggs, 2011). Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration amongst all stakeholders are central to adaptive water management. However, although climate change is frequently cited as a key motive, there is very little published guidance on how to implement the adaptive water management approach. Some examples are given in Ludwig et al. (2009). The most comprehensive overview of adaptive water

Table 3-3 | Categories of climate change adaptation options for the management of freshwater resources.

Category	Option	May assist both adaptation and mitigation
Institutional	Support integrated water resources management, including the integrated management of land considering specifically negative and positive impacts of climate change	X
	Promote synergy of water and energy savings and efficient use	X
	Identify "low-regret policies" and build a portfolio of relevant solutions for adaptation	X
	Increase resilience by forming water utility network working teams	
	Build adaptive capacity	
	Improve and share information	X
	Adapt the legal framework to make it instrumental for addressing climate change impacts	X
	Develop financial tools (credit, subsidies, and public investment) for the sustainable management of water, and for considering poverty eradication and equity	
Design and operation	Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	
	Revise design criteria of water infrastructure to optimize flexibility, redundancy, and robustness	
	Ensure plans and services are robust, adaptable, or modular; give good value; are maintainable; and have long-term benefits, especially in low-income countries	X
	Operate water infrastructure so as to increase resilience to climate change for all users and sectors	
	When and where water resources increase, alter dam operations to allow freshwater ecosystems to benefit	
	Take advantage of hard and soft adaptation measures	X
	Carry out programs to protect water resources in quantity and quality	
	Increase resilience to climate change by diversifying water sources[a] and improving reservoir management	X
	Reduce demand by controlling leaks, implementing water-saving programs, cascading and reusing water	X
	Improve design and operation of sewers, sanitation, and wastewater treatment infrastructure to cope with variations in influent quantity and quality	
	Provide universal sanitation with technology locally adapted, and provide for proper disposal and reintegration of used water into the environment or for its reuse	
Reduce impact of natural disasters	Implement monitoring and early warning systems	
	Develop contingency plans	
	Improve defenses and site selection for key infrastructure that is at risk of floods	
	Design cities and rural settlements to be resilient to floods	
	Seek and secure water from a diversity (spatially and source-type) of sources to reduce impacts of droughts and variability in water availability	
	Promote both the reduction of water demand and the efficient use of water by all users	
	Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
	Plant flood- or drought-resistant crop varieties	
Agricultural irrigation	Improve irrigation efficiency and reduce demand for irrigation water	X
	Reuse wastewater to irrigate crops and use soil for carbon sequestration	X
Industrial use	When selecting alternative sources of energy, assess the need for water	X
	Relocate water-thirsty industries and crops to water-rich areas	
	Implement industrial water efficiency certifications	X

[a]This includes water reuse, rain water harvesting, and desalination, among others.

Sources: Vörösmarty et al. (2000); Marsalek et al. (2006); Mogaka et al. (2006); Dillon and Jiménez (2008); Jiménez and Asano (2008); Keller (2008); McCafferty (2008); McGuckin (2008); Seah (2008); UN-HABITAT (2008); Thöle (2008); Andrews (2009); Bahri (2009); Munasinghe (2009); NACWA (2009); OFWAT (2009); Reiter (2009); Whitehead et al. (2009b); de Graaf and der Brugge (2010); Dembo (2010); Godfrey et al. (2010); Howard et al. (2010); Mackay and Last (2010); Mukhopadhyay and Dutta (2010); OECD (2010); Renofalt et al. (2010); Zwolsman et al. (2010); Arkell (2011a, 2011b); Elliott et al. (2011); Emelko et al. (2011); Jiménez (2011); Kingsford (2011); Major et al. (2011); Sprenger et al. (2011); UNESCO (2011); Wang X. et al. (2011); Bowes et al. (2012).

management that explicitly incorporates climate change and its uncertainty is the three-step framework of the U.S. Water Utilities Climate Alliance (WUCA, 2010): system vulnerability assessment, utility planning using decision-support methods, and decision making and implementation. Planning methods for decision support include classic decision analysis, traditional scenario planning, and robust decision making (Lempert et al., 1996, 2006; Nassopoulos et al., 2012). The latter was applied by the Inland Empire Utilities Agency, supplying water to a region in Southern California (Lempert and Groves, 2010). This led to the refinement of the company's water resource management plan, making it more robust to three particularly challenging aspects of climate change that were identified by the scenario analysis. Another framework, based on risk assessment, is the threshold-scenario framework of Freas et al. (2008).

3.6.3. Costs of Adaptation to Climate Change

Calculating the global cost of adaptation in the water sector is a difficult task and results are highly uncertain. Globally, to maintain water services at non-climate change levels to the year 2030 in more than 200 countries, total adaptation costs for additional infrastructure were estimated as US$531 billion for the SRES A1B scenario (Kirshen, 2007). Including two further costs, for reservoir construction because the best locations have already been taken, and for unmet irrigation demands, total water sector adaptation costs were estimated as US$225 billion, or US$11 billion per year for the SRES A1B scenario (UNFCCC, 2007).

Average annual water supply and flood protection costs to 2050 for restoring service to non-climate change levels were estimated to be US$19.7 billion for a dry GCM projection of the SRES A2 scenario and US$14.4 billion for a wet GCM projection (Ward et al., 2010; World Bank, 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US$13.0 billion (dry) and US$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for about 50% of total global adaptation cost, which was distributed regionally in the proportions: East Asia/Pacific, 20%; Europe/Central Asia, 10%; Latin America/Caribbean, 20%; Middle East/North Africa, 5%; South Asia, 20%; sub-Saharan Africa, 20%.

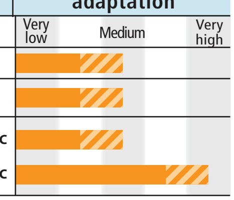
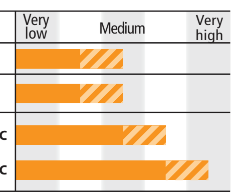
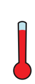
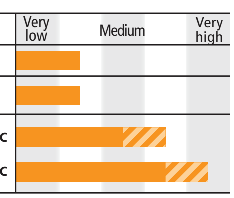
Annual costs for adaptation to climate change in sub-Saharan Africa are estimated as US$1.1 to 2.7 billion for current urban water infrastructure, plus US$1.0 to 2.5 billion for new infrastructure to meet the 2015 Millennium Development Goals (Muller, 2007). These estimates assume a 30% reduction in stream flow and an increase of at least 40% in the unit cost of water. Annual estimates of adaptation costs for urban water storage are US$0.05 to 0.15 billion for existing facilities and US$0.015 to 0.05 billion for new developments. For wastewater treatment, the equivalent estimates are US$0.1 to 0.2 billion and US$0.075 to 0.2 billion.

3.6.4. Adaptation in Practice in the Water Sector

A number of water management agencies are beginning to factor climate change into processes and decisions (Kranz et al., 2010; Krysanova et al., 2010), with the amount of progress strongly influenced by institutional characteristics. Most of the work has involved developing methodologies to be used by water resources and flood managers (e.g., Rudberg et al., 2012), and therefore represents attempts to improve adaptive capacity. In England and Wales, for example, methodologies to gauge the effects of climate change on reliability of water supplies have evolved since the late 1990s (Arnell, 2011), and the strategic plans of water supply companies now generally allow for climate change. Brekke et al. (2009a) describe proposed changes to practices in the USA. Several studies report community-level activities to reduce exposure to current hydrological variability, regarded explicitly as a means of adapting to future climate change (e.g., Barrios et al., 2009; Gujja et al., 2009; Kashaigili et al., 2009; Yu et al., 2009).

Table 3-4 | Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here assessed over 2030–2040), and longer term (here assessed over 2080–2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.

Climate-related drivers of impacts			Level of risk & potential for adaptation
 Warming trend	 Drying trend	 Extreme precipitation	

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Flood risks associated with climate change increase with increasing greenhouse gas emissions. (*robust evidence, high agreement*) [3.4.8]	By 2100, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6).		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions. (*robust evidence, high agreement*) [3.5.1]	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy, and food security.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter. (*robust evidence, high agreement*) [3.4.3]	Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

Frequently Asked Questions
FAQ 3.4 | Does climate change imply only bad news about water resources?

There is good news as well as bad about water resources, but the good news is very often ambiguous. Water may become less scarce in regions that get more precipitation, but more precipitation will probably also increase flood risk; it may also raise the groundwater table, which could lead to damage to buildings and other infrastructure or to reduced agricultural productivity due to wet soils or soil salinization. More frequent storms reduce the risk of eutrophication and algal blooms in lakes and estuaries by flushing away nutrients, but increased storm runoff will carry more of those nutrients to the sea, exacerbating eutrophication in marine ecosystems, with possible adverse impacts as discussed in Chapter 30. Water and wastewater treatment yields better results under warmer conditions, as chemical and biological reactions needed for treatment perform in general better at higher temperatures. In many rivers fed by glaciers, there will be a "meltwater dividend" during some part of the 21st century, due to increasing rates of loss of glacier ice, but the continued shrinkage of the glaciers means that after several decades the total amount of meltwater that they yield will begin to decrease (*medium confidence*). An important point is that often impacts do not become "good news" unless investments are made to exploit them. For instance, where additional water is expected to become available, the infrastructure to capture that resource would need to be developed if it is not already in place.

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

Adaptation in other sectors such as agriculture, forestry, and industry might have impacts on the freshwater system, and therefore needs to be considered while planning adaptation in the water sector (Jiang et al., 2013). For example, better agricultural land management practices can also reduce erosion and sedimentation in river channels (Lu et al., 2010), while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream (World Bank, 2007). A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems

Many measures for climate change mitigation affect freshwater systems. Afforestation generally increases evapotranspiration and decreases total runoff (van Dijk and Keenan, 2007). Afforestation of areas deemed suitable according to the Clean Development Mechanism–Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to large and spatially extensive decreases of long-term average runoff (Trabucco et al., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases of 80 to 100% were computed, mostly in semiarid areas (Trabucco et al., 2008). For example, economic incentives for carbon sequestration may encourage the expansion of *Pinus radiata* timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity; afforestation is viable to the forestry industry only because it pays less than 1% of the actual cost of streamflow reduction caused by replacing Fynbos by the plantations (Chisholm, 2010). In general, afforestation has beneficial impacts on soil erosion, local flood risk, water quality (nitrogen, phosphorus, suspended sediments), and stream habitat quality (van Dijk and Keenan, 2007; Trabucco et al., 2008; Wilcock et al., 2008).

Irrigated bioenergy crops and hydropower can have negative impacts on freshwater systems (Jacobson, 2009). In the USA, water use for irrigating biofuel crops could increase from 2% of total water consumption in 2005 to 9% in 2030 (King et al., 2010). Irrigating some bioenergy crops may cost more than the energy thus gained. In dry parts of India, pumping from a depth of 60 m for irrigating jatropha is estimated to consume more energy than that gained from the resulting higher crop yields (Gupta et al., 2010). For a biofuel scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; biofuel production is projected to increase water consumption significantly in some countries (e.g., Germany, Italy, and South Africa), and to exacerbate the already serious water scarcity in others (e.g., Spain and China) (Gerbens-Leenes et al., 2012). Conversion of native Caatinga forest into rainfed fields for biofuels in semiarid northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is a risk of soil salinization due to rising groundwater tables.

Hydropower generation leads to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll and Zhang, 2010; Poff and Zimmerman, 2010), and to fragmentation of river channels by dams, with negative impacts on migratory species (Bourne et al., 2011). Hydropower operations often lead to discharge changes on hourly timescales that are detrimental to the downstream river ecosystem (Bruno et al., 2009; Zimmerman et al., 2010). However, release management and structural measures like fish ladders can mitigate these negative impacts somewhat (Williams, 2008). In tropical regions, the global warming potential of hydropower, due to methane emissions from man-made reservoirs, may exceed that of thermal power; based on observed emissions of a tropical reservoir, this might be the case where the ratio of hydropower generated to the surface area of the reservoir is less than 1 MW km^{-2} (Gunkel, 2009).

CO_2 leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1 to 2 units and increase concentrations of metals, uranium, and barium (Little and Jackson, 2010). Pressure exerted by gas injection can push brines or brackish water into freshwater parts of the aquifer (Nicot, 2008). Displacement of brine into potable water was not considered in a screening methodology for CCS sites in the Netherlands (Ramírez et al., 2010). Another emergent freshwater-related risk of climate mitigation is increased natural gas extraction from low-permeability rocks. The required hydraulic fracturing process ("fracking") uses large amounts of water (a total of about 9000 to 30,000 m^3 per well, mixed with a number of chemicals), of which a part returns to the surface (Rozell and Reaven, 2012). Fracking is suspected to lead to pollution of the overlying freshwater aquifer or surface waters, but appropriate observations and peer-reviewed studies are still lacking (Jackson et al., 2013). Densification of urban areas to reduce traffic emissions is in conflict with providing additional open space for inundation in case of floods (Hamin and Gurran, 2009).

3.7.2.2. Impact of Water Management on Climate Change Mitigation

A number of water management decisions affect GHG emissions. Water demand management has a significant impact on energy consumption because energy is required to pump and treat water, to heat it, and to treat wastewater. For example, water supply and water treatment were responsible for 1.4% of total electricity consumption in Japan in 2008 (MLIT, 2011). In the USA, total water-related energy consumption was equivalent to 13% of total electricity production in 2005, with 70% for water heating, 14% for wastewater treatment, and only 5% for pumping of irrigation water (Griffiths-Sattenspiel and Wilson, 2009). In China, where agriculture accounts for 62% of water withdrawals, groundwater pumping for irrigation accounted for only 0.6% of China's GHG emissions in 2006, a small fraction of the 17 to 20% share of agriculture as a whole (Wang et al., 2012). Where climate change reduces water resources in dry regions, desalination of seawater as an adaptation option is expected to increase GHG emissions if carbon-based fuels are used as energy source (McEvoy and Wilder, 2012).

In Southeast Asia, emissions due to peatland drainage contribute 1.3 to 3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer et al., 2010), and peatland rewetting could substantially reduce net GHG emissions (Couwenberg et al., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality and biodiversity (House et al., 2010). Irrigation can increase CO_2 storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semiarid California did not significantly increase soil organic carbon (Wu et al., 2008). Water management in rice paddies can reduce methane (CH_4) emissions. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global CH_4 emissions from rice fields could be decreased by 4.1 Tg yr^{-1} (16% around the year 2000), and nitrous oxide (N_2O) emissions would not increase significantly (Yan et al., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, but data records are unevenly available and unevenly distributed geographically. Information on many other relevant variables, such as soil moisture, snow depth, groundwater depth, and water quality, is particularly limited in developing countries. Relevant socioeconomic data, such as rates of surface water and groundwater withdrawal by each sector, and information on already implemented adaptations for stabilizing water supply, such as long-range diversions, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly (see Box CC-VW).

Relatively little is known about the economic aspects of climate change impacts and adaptation options related to water resources. For example, regional damage curves need to be developed, relating the magnitudes of major water related disasters (such as intense precipitation and surface soil dryness) to the expected costs.

There is a continuing, although narrowing, mismatch between the large scales resolved by climate models and the catchment scale at which water is managed and adaptations must be implemented. Improving the spatial resolution of regional and global climate models, and the accuracy of methods for downscaling their outputs, can produce information more relevant to water management, although the robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. More computing capacity is needed to address these problems with more ensemble simulations at high spatial resolution. More research is also needed into novel ways of combining different approaches to projection of plausible changes in relevant climate variables so as to provide robust information to water managers. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation. In addition, there is a difficulty to model and interpret results obtained from applying models at different scales and with different logics to follow the future changes on water quality. Moreover, the establishment of a proper baseline to isolate the effects derived from climate change from the anthropogenic cause is a major challenge.

Interactions among socio-ecological systems are not yet well considered in most impact assessments. Particularly, there are few studies on the impacts of mitigation and adaptation in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land surface components of climate models, to data on water management activities such as reservoir operations, irrigation, and urban withdrawals from surface water or groundwater.

To support adaptation by increasing reliance on groundwater and on the coordinated and combined use of groundwater and surface water, ground-based data are needed in the form of a long-term program to monitor groundwater dynamics and stored groundwater volumes. Understanding of groundwater recharge and groundwater surface water interactions, particularly by the assessment of experiences of conjunctive use of groundwater and surface water, needs to be better developed.

More studies are needed, especially in developing countries, on the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

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4 Terrestrial and Inland Water Systems

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Frequently Asked Questions

Executive Summary

The planet's biota and ecosystem processes were strongly affected by past climate changes at rates of climate change lower than those projected during the 21st century under high warming scenarios (e.g., Representative Concentration Pathway 8.5 (RCP8.5)) (*high confidence*). Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5 were associated with species extinctions in some groups (*high confidence*). {4.2.3}

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and RCP8.5 (*high confidence*). Direct human impacts such as land use and land use change, pollution, and water resource development will continue to dominate the threats to most freshwater (*high confidence*) and terrestrial (*medium confidence*) ecosystems globally over the next 3 decades. Changing climate exacerbates other impacts on biodiversity (*high confidence*). Ecosystem changes resulting from climate change may not be fully apparent for several decades, owing to long response times in ecological systems (*medium confidence*). Model-based projections imply that under low to moderate warming scenarios (e.g., RCP2.6 to RCP6.0), direct land cover change will continue to dominate over (and conceal) climate-induced change as a driver of ecosystem change at the global scale; for higher climate change scenarios, some model projections imply climate-driven ecosystem changes sufficiently extensive to equal or exceed direct human impacts at the global scale (*medium confidence*). In high-altitude and high-latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function, especially in the second half of the 21st century (*high confidence*). {4.2.4, 4.3.2.5, 4.3.3, 4.3.3.1, 4.3.3.3, 4.4.1.1}

When terrestrial ecosystems are substantially altered (in terms of plant cover, biomass, phenology, or plant group dominance), either through the effects of climate change or through other mechanisms such as conversion to agriculture or human settlement, the local, regional, and global climates are also affected (*high confidence*). The feedbacks between terrestrial ecosystems and climate include, among other mechanisms, changes in surface albedo, evapotranspiration, and greenhouse gas (GHG) emissions and uptake. The physical effects on the climate can be opposite in direction to the GHG effects, and can materially alter the net outcome of the ecosystem change on the global climate (*high confidence*). The regions where the climate is affected may extend beyond the location of the ecosystem that has changed. {4.2.4.1, 4.3.3.4}

Rising water temperatures, due to global warming, will lead to shifts in freshwater species distributions and worsen water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients (*high confidence*). Climate change-induced changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins (*medium confidence*). {4.3.3.3, Box CC-RF}

Many plant and animal species have moved their ranges, altered their abundance, and shifted their seasonal activities in response to observed climate change over recent decades (*high confidence*). They are doing so now in many regions and will continue to do so in response to projected future climate change (*high confidence*). The broad patterns of species and biome shifts toward the poles and higher in altitude in response to a warming climate are well established for periods thousands of years in the past (*very high confidence*). These general patterns of range shifts have also been observed over the last few decades in some well-studied species groups such as insects and birds and can be attributed to observed climatic changes (*high confidence*). Interactions between changing temperature, precipitation, and land use can sometimes result in range shifts that are downhill or away from the poles. Certainty regarding past species movements in response to changing climate, coupled with projections from a variety of models and studies, provides *high confidence* that such species movements will be the norm with continued warming. Under all RCP climate change scenarios for the second half of the 21st century, with *high confidence*: (1) community composition will change as a result of decreases in the abundances of some species and increases in others; and (2) the seasonal activity of many species will change differentially, disrupting life cycles and interactions between species. Composition and seasonal change will both alter ecosystem function. {4.2.1, 4.2.3, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3, 4.4.1.1}

Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, RCP6.0, and RCP8.5 scenarios) (*medium confidence*). The climate velocity (the rate of movement of the climate across the landscape) will exceed the maximum velocity at which many groups of organisms, in many situations, can disperse or migrate, except after mid-century in the RCP2.6 scenario. Populations of species that cannot keep up with their climate niche will find themselves in unfavorable climates, unable to reach areas of potentially suitable climate. Species occupying extensive flat landscapes are particularly vulnerable because they must disperse over longer distances than species in mountainous regions to keep pace with shifting climates. Species with low dispersal capacity will also be especially vulnerable: examples include many plants (especially trees), many amphibians, and some small mammals. For example, the maximum observed and modeled dispersal and establishment rates for mid- and late-successional tree species are insufficient to track climate change except in mountainous areas, even at moderate projected rates of climate change. Barriers to dispersal, such as habitat fragmentation, prior occupation of habitat by competing species, and human-made impediments such as dams on rivers and urbanized areas on land, reduce the ability of species to migrate to more suitable climates (*high confidence*). Intentional and accidental anthropogenic transport can speed dispersal. {4.3.2.5, 4.3.3.3}

Large magnitudes of climate change will reduce the populations, vigor, and viability of species with spatially restricted populations, such as those confined to small and isolated habitats, mountaintops, or mountain streams, even if the species has the biological capacity to move fast enough to track suitable climates (*high confidence*). The adverse effects on restricted populations are modest for low magnitudes of climate change (e.g., RCP2.6) but very severe for the highest magnitudes of projected climate change (e.g., RCP8.5). {4.3.2.5, 4.3.3.4, 4.3.4.1}

The capacity of many species to respond to climate change will be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of inhospitable land uses, habitat fragmentation and loss, competition with alien species, exposure to new pests and pathogens, nitrogen loading, and tropospheric ozone. {4.2.4.6, 4.3.3.5, Figure 4-4}

The establishment, growth, spread, and survival of populations of invasive alien species have increased (*high confidence*), but the ability to attribute alien species invasion to climate change is low in most cases. Some invasive alien species have traits that favor their survival and reproduction under changing climates. Future movement of species into areas where they were not present historically will continue to be driven mainly by increased dispersal opportunities associated with human activities and by increased disturbances from natural and anthropogenic events, in some cases facilitated and promoted by climate change. {4.2.4.6, Figure 4-4}

A large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, overexploitation, pollution, and invasive species (*high confidence*). The extinction risk is increased under all RCP scenarios, and the risk increases with both the magnitude and rate of climate change. While there is *medium confidence* that recent warming contributed to the extinction of some species of Central American amphibians, there is generally *very low confidence* that observed species extinctions can be attributed to recent climate change. Models project that the risk of species extinctions will increase in the future owing to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic focus for such extinctions and the time frame over which extinctions could occur. Modeling studies and syntheses since the AR4 broadly confirm that a large proportion of species are projected to be at increased risk of extinction at all but the lowest levels of climate warming (RCP2.6). Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. {4.3.2.5}

Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO_2) emitted to the atmosphere by human activities in the past 3 decades (*high confidence*). The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability; as a result there is *low confidence* in the ability to determine whether the net rate at which carbon has been taken up by terrestrial ecosystems at the global scale has changed between the decades 1991–2000 and 2001–2010. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, nitrogen deposition, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. {4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2, 4.3.2.3, WGI AR5 6.3.1, 6.3.2.6}

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal time scale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss back to the atmosphere as a result of the direct and indirect effects of climate change, deforestation, and degradation (*high confidence*). The net transfer of CO_2 from the atmosphere to the land is projected to weaken during the 21st century (*medium confidence*). The direct effects of climate change on stored terrestrial carbon include high temperatures, drought, and windstorms; indirect effects include increased risk of fires and pest and disease outbreaks. Experiments and modeling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate; and *high confidence* that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO_2. There is *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity by amounts comparable in magnitude to the enhancement by rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors. {4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3}

Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Changes in the ecosystem disturbance regime beyond the range of natural variability will alter the structure, composition, and functioning of ecosystems (*high confidence*). Ecological theory and experimentation predict that ecological change resulting from altered disturbance regimes will be manifested as relatively abrupt and spatially patchy transitions in ecosystem structure, composition, and function, rather than gradual and spatially uniform shifts in location or abundance of species (*medium confidence*). {4.2.4.6, 4.3.3, 4.3.2.5, Box 4-3, Box 4-4, Figure 4-10}

Increased tree death has been observed in many places worldwide, and in some regions has been attributed to climate change (*high confidence*). In some places it is sufficiently intense and widespread as to result in forest dieback (*low confidence*). Forest dieback is a major environmental risk, with potentially large impacts on climate, biodiversity, wood production, water quality, amenity, and economic activity. In detailed regional studies in western and boreal North America, the tree mortality observed over the past few decades has been attributed to the effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming (*high confidence*). Tree mortality and associated forest dieback will become apparent in many regions sooner than previously anticipated (*medium confidence*). Earlier projections of increased tree growth and enhanced forest carbon sequestration due to increased growing season duration, rising CO_2 concentration, and atmospheric nitrogen deposition must be balanced by observations and projections of increasing tree mortality and forest loss due to fires and pest attacks. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, depending on the balance of the positive versus negative effects of global change. {4.3.2, 4.3.3.1, 4.3.3.4, 4.3.3.5, 4.3.4, 4.3.4.2, Box 4-2, Box 4-3}

There is a high risk that the large magnitudes and high rates of climate change associated with low-mitigation climate scenarios (RCP4.5 and higher) will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon (*low confidence*) and Arctic (*medium confidence*), leading to substantial additional climate change. There are plausible mechanisms, supported by experimental evidence, observations, and model results, for the existence of ecosystem tipping points in both boreal-tundra Arctic systems and the rainforests of the Amazon basin. Continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of GHGs (*medium confidence*). Adaptation measures will be unable to prevent substantial change in the boreal-Arctic system (*high confidence*). Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century a (*medium confidence*), but a projected increase in severe drought episodes, together with land use change and forest fire, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems, and in doing so put a large stock of biodiversity at elevated risk, while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). {4.2.4.1, 4.3.3.1.1, 4.3.3.1.3, 4.3.3.4, Figure 4-8, Box 4-3, Box 4-4}

Management actions can reduce, but not eliminate, the risk of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species it will be insufficient to cope with projected rates and magnitudes of climate change in the 21st century without substantial loss of species and ecosystem services, under medium-range warming (e.g., RCP6.0) or high-range warming scenarios (e.g., RCP8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of climate change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. {4.4, 4.4.1, 4.4.2}

Adaptation responses to climate change in the urban and agricultural sectors can have unintended negative outcomes for terrestrial and freshwater ecosystems (*medium confidence*). For example, adaptation responses to counter increased variability of water supply, such as building more and larger impoundments and increased water extraction, will in many cases worsen the direct effects of climate change in freshwater ecosystems. {4.3.3.3, 4.3.4.6}

Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). For example, the land use scenario accompanying the mitigation scenario RCP2.6 features a large expansion of biofuel production, displacing natural forest cover. {4.2.4.1, 4.4.4}

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in WGII AR4 Chapters 3 (Kundzewicz et al., 2007) and 4 (Fischlin et al., 2007), but also in WGII AR4 Sections 1.3.4 and 1.3.5 (Rosenzweig et al., 2007). The WGII AR4 SPM stated "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases," though they noted that documentation of observed changes in tropical regions and the Southern Hemisphere was sparse (Rosenzweig et al., 2007). Fischlin et al. (2007) found that 20 to 30% of the plant and animal species that had been assessed to that time were considered to be at increased risk of extinction if the global average temperature increase exceeds 2°C to 3°C above the preindustrial level with *medium confidence*, and that substantial changes in structure and functioning of terrestrial, marine, and other aquatic ecosystems are *very likely* under that degree of warming and associated atmospheric CO_2 concentration. No time scale was associated with these findings. The carbon stocks in terrestrial ecosystems were considered to be at high risk from climate change and land use change. The report warned that the capacity of ecosystems to adapt naturally to the combined effect of climate change and other stressors is likely to be exceeded if greenhouse gas (GHG) emission continued at or above the then-current rate.

4.2. A Dynamic and Inclusive View of Ecosystems

There are three aspects of the contemporary scientific view of ecosystems that are important to know for policy purposes. First, ecosystems usually have imprecise and variable boundaries. They span a wide range of spatial scales, nested within one another, from the whole biosphere, down through its major ecosystem types (biomes), to local and possibly short-lived associations of organisms. Second, the human influence on ecosystems is globally pervasive. Humans are regarded as an integral, rather than separate, part of social-ecological systems (Gunderson and Holling, 2001; Berkes et al., 2003). Ecosystems are connected across boundaries through the movement of energy, materials, and organisms, and subsidies between terrestrial and freshwater systems are known to be particularly important (Polis et al., 1997; Loreau et al., 2003). As a consequence, human activities in terrestrial systems can significantly impact freshwater ecosystems and their biota (Allan, 2004). The dynamics of socio-ecological systems are governed not only by biophysical processes such as energy flows, material cycles, competition, and predation, but also by social processes such as economics, politics, culture, and individual preferences (Walker and Salt, 2006). Third, ecologists do not view ecosystems as necessarily inherently static and at equilibrium in the absence of a human disturbance (Hastings, 2004). Ecosystems vary over time and space in the relative magnitude of their components and fluxes, even under a constant environment, owing to internal dynamics (Scheffer, 2009). Furthermore, attempts to restrict this intrinsic variation—or that resulting from externally generated disturbances—are frequently futile, and may damage the capacity of the ecosystem to adapt to a changing environment (Folke et al., 2004). This contrasts with the popular view that ecosystems exhibit a "balance of Nature" and benefit from being completely protected from disturbance.

4.2.1. Ecosystems, Adaptation, Thresholds, and Tipping Points

The term "adaptation" has different meanings in climate policy, ecology, and evolutionary biology. In climate policy (see Glossary) it implies human actions intended to reduce negative outcomes. In ecology, ecosystems are said to be adaptive because their composition or function can change in response to a changing environment, without necessarily involving deliberate human actions (see Section 4.4.1). In evolutionary biology, adaptation means a change in the genetic properties of a population of individuals as a result of natural selection (Section 4.4.1.2), a possibility seen since the Fourth Assessment Report as increasingly relevant to climate change.

The notion of thresholds has become a prominent ecological and political concern (Knapp, A.K. et al., 2008; Lenton et al., 2008; Leadley et al., 2010). To avoid policy confusion, three types of threshold need to be distinguished. The first reflects a human preference that the ecosystem stays within certain bounds, such as above a certain forest cover. These can be, by definition, negotiated. The second type reflects fundamental biological or physical properties, for instance the temperature at which frozen soils thaw (see Box 4-4) or the physiological tolerance limits of species. The third type is caused by system dynamics: the point at which the net effect of all the positive and negative feedback loops regulating the system is sufficiently large and positive that a small transgression becomes sufficiently amplified to lead to a change in ecosystem state called a regime shift (Lenton et al., 2008). The new state exhibits different dynamics, mean composition, sensitivity to environmental drivers, and flows of ecosystem services relative to the prior state. This type of threshold is called a "tipping point" (defined in the Glossary as a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated) and is important in the context of climate change because its onset may be abrupt, hard to predict precisely, and effectively irreversible (Scheffer et al., 2009; Leadley et al., 2010; Barnosky et al., 2012; Brook et al., 2013; Hughes et al., 2013). Many examples of tipping points have now been identified (Scheffer, 2009). Regional-scale ecosystem tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (Section 4.2.3) and there is concern that they could occur in the near future (see Boxes 4-3 and 4-4).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold. In practice, such signals may not be detectable against background noise and uncertainty until the threshold is crossed (Biggs et al., 2009). The dynamics of ecosystems are complex and our present level of knowledge is inadequate to predict all ecosystem outcomes with confidence, even if the future climate were precisely known.

Field observations over the past century in numerous locations in boreal, temperate, and tropical ecosystems have detected biome shifts, the replacement at a location of one suite of species by another (*high confidence*). The effect is usually of biomes moving upward in elevation and to higher latitudes (Gonzalez et al., 2010; see Figure 4-1). These shifts

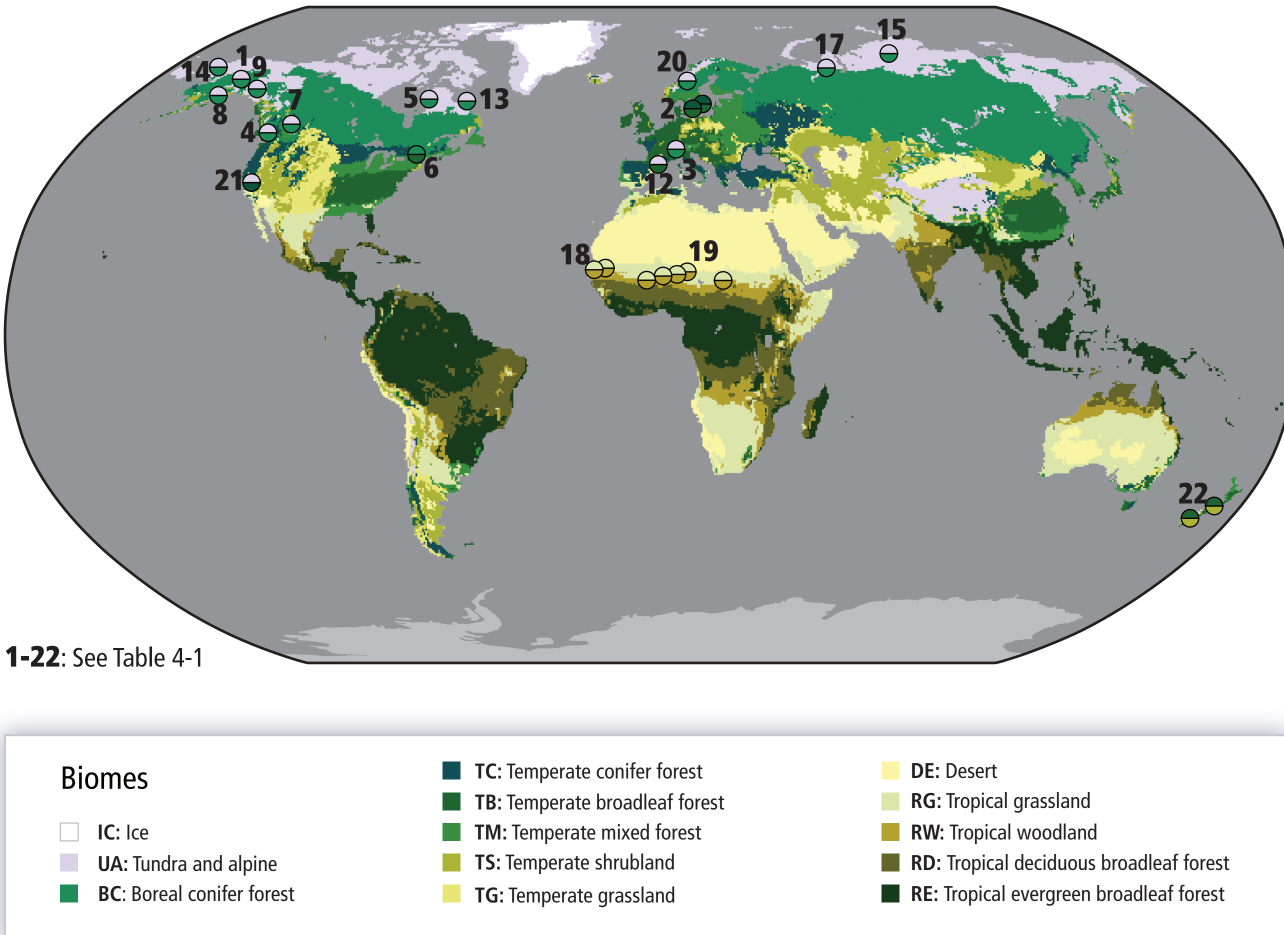

Figure 4-1 | Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez et al. (2010). The color of each semicircle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961–1990 climate. No shift was observed on locations 10, 11, 16, and 23 (see Table 4-1).

have often been attributed to anthropogenic climate change, as biome distribution is known to broadly reflect climate zones, and the shifts have been observed in areas without major human disturbance (*medium confidence*; see Table 4-1). Projections of future vegetation distribution under climate change indicate that many biomes could shift substantially, including in areas where ecosystems are largely undisturbed by direct human land use (Figure 4-2). The extent of the shift increases with increasing global mean warming, without a sudden threshold (Scholze et al., 2006; Pereira et al., 2010; Rehfeldt et al., 2012).

4.2.2. Methods and Models Used

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or elsewhere in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis. Studies of the relatively distant past are discussed in depth in Section 4.2.3. Inferences from present spatial patterns in relation to climate is at the core of climate envelope niche modeling, a well-established but limited statistical technique for making projections of the future distribution under equilibrium conditions (Elith and Leathwick, 2009). Representing the rate of change during the non-equilibrium conditions that will prevail over the next century requires a more mechanistic approach, of which there are some examples (e.g., Keith et al., 2008; Kearney and Porter, 2009). Changes in ecosystem function are usually determined by experimentation (see examples in Section 4.3.3) and are modeled using mechanistic models, in many cases with relatively high uncertainty (Seppelt et al., 2011).

4.2.3. Paleoecological Evidence

Paleoclimatic observations and modeling indicate that the Earth's climate has always changed on a wide range of time scales. In many cases, particularly over the last million years, it has changed in ways that are well understood in terms of both patterns and causes (Jansen et al., 2007; see WGI AR5 Chapter 5). Paleoecological records demonstrate with *high confidence* that the planet's biota (both terrestrial and aquatic),

Table 4-1 | Biome shifts of the 20th century from published field research that examined trends over periods >30 years for biomes in areas where climate (rather than land use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez et al., 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901–2002 data (Mitchell and Jones, 2005; Gonzalez et al., 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. *Rate significant at P ≤ 0.05.

Location	Reference	Plots	Time period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century^{-1})	Precip. change (% century^{-1})
1. Alaska Range, Alaska, USA	Lloyd and Fastie (2003)	18	1800–2000	L	UA	BC	1.1*	3
2. Baltic Coast, Sweden	Walther et al. (2005)	7	1944–2003	L	TC	TB	0.6*	8
3. Becca di Viou, Italy	Leonelli et al. (2011)	1	1700–2008	E	UA	BC	0.9*	–6
4. Garibaldi, British Columbia, Canada	Brink (1959)	1	1860–1959	E	UA	BC	0.7*	16*
5. Goulet Sector, Québec, Canada	Payette and Filion (1985)	2	1880–1980	E	UA	BC	1.4*	19*
6. Green Mountains, Vermont, USA	Beckage et al. (2008)	33	1962–2005	E	BC	TB	1.6*	6
7. Jasper, Alberta, Canada	Luckman and Kavanagh (2000)	1	1700–1994	E	UA	BC	0.6	21*
8. Kenai Mountains, Alaska, USA	Dial et al. (2007)	3	1951–1996	E	UA	BC	0.7	6
9. Kluane Range, Yukon, Canada	Danby and Hik (2007)	2	1800–2000	E	UA	BC	0.7	5
10. Low Peninsula, Québec, Canada	Payette and Filion (1985)	1	1750–1980	N	—	—	1.4*	19*
11. Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald (1995)	13	1700–1990	N	—	—	1.4*	3
12. Montseny Mountains, Catalonia, Spain	Peñuelas and Boada (2003)	50	1945–2001	E	UA	TB	1.2*	–3
13. Napaktok Bay, Labrador, Canada	Payette (2007)	2	1750–2000	L	UA	BC	1.1*	5
14. Noatak, Alaska, USA	Suarez et al. (1999)	18	1700–1990	L	UA	BC	0.6	19*
15. Putorana Mountains, Russian Federation	Kirdyanov et al. (2012)	10	1500–2000	E	UA	BC	0.3	10
16. Rahu Saddle, New Zealand	Cullen et al. (2001)	7	1700–2000	N	—	—	0.6*	3
17. Rai-Iz, Urals, Russian Federation	Devi et al. (2008)	144	1700–2002	E	UA	BC	0.3	35*
18. Sahel, Sudan, Guinea zones; Senegal	Gonzalez (2001)	135	1945–1993	L	RW	RG	0.4*	–48*
19. Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez et al. (2012)	14	1960–2000	L	RW	RG	–0.01* to 0.8*	–31* to 9
20. Scandes, Sweden	Kullman and Öberg (2009)	123	1915–2007	E	UA	BC	0.8*	25*
21. Sierra Nevada, California, USA	Millar et al. (2004)	10	1880–2002	E	UA	TC	–0.1	21*
22. South Island, New Zealand	Wardle and Coleman (1992)	22	1980–1990	E	TS	TB	0.6*	3
23. Yambarran, Northern Territory, Australia	Sharp and Bowman (2004)	33	1948–2000	N	—	—	–0.06	35*

carbon cycle, and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as that projected during the 21st century under mid- to high-end radiative forcing pathways (e.g., MacDonald et al., 2008; Claussen, 2009; Arneth et al., 2010; Dawson et al., 2011; Willis and MacDonald, 2011). Excellent examples of past large climate change events that drove large ecological change, as well as recovery periods in excess of a million years, include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, about 443 Ma, the Devonian, about 359 Ma, the Permian, about 251 Ma, the Triassic, about 200 Ma, and the Cretaceous, about 65 Ma; Barnosky et al., 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing et al., 2005; Jaramillo et al., 2010; Wing and Currano, 2013), the early Eocene Climatic Optimum (EECO, 53 to 50 Ma; Woodburne et al., 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood et al., 2011), and the Last Glacial Maximum (LGM) to Holocene transition between 21 and 6 ka (MacDonald et al., 2008; Clark et al., 2009; Gill et al., 2009; Williams, J.W. et al., 2010; Prentice et al., 2011; Daniau et al., 2012). The paleoecological record thus provides *high confidence* that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7 to 12.9 ka) provides a relatively recent analogy for climate change at a rate approaching, for many regions, that projected for the 21st century for all Representative Concentration Pathways (RCPs; Alley et al., 2003; Steffensen et al., 2008). Ecosystems and species responded rapidly during the Younger Dryas by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by human activities (Gill et al., 2009; Dawson et al., 2011). In some regions, species became locally or regionally extinct (extirpated), but there is no evidence for climate-driven global-scale extinctions during this period (Botkin et al., 2007; Willis, K.J. et al., 2010). However, the Younger Dryas climate changes differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley et al., 2003). The mid-Holocene, about 6 ka, provides a very recent example of the effects of modest climate change. Regional mean warming during this period (mean annual temperature about 0.5°C to 1.0°C above

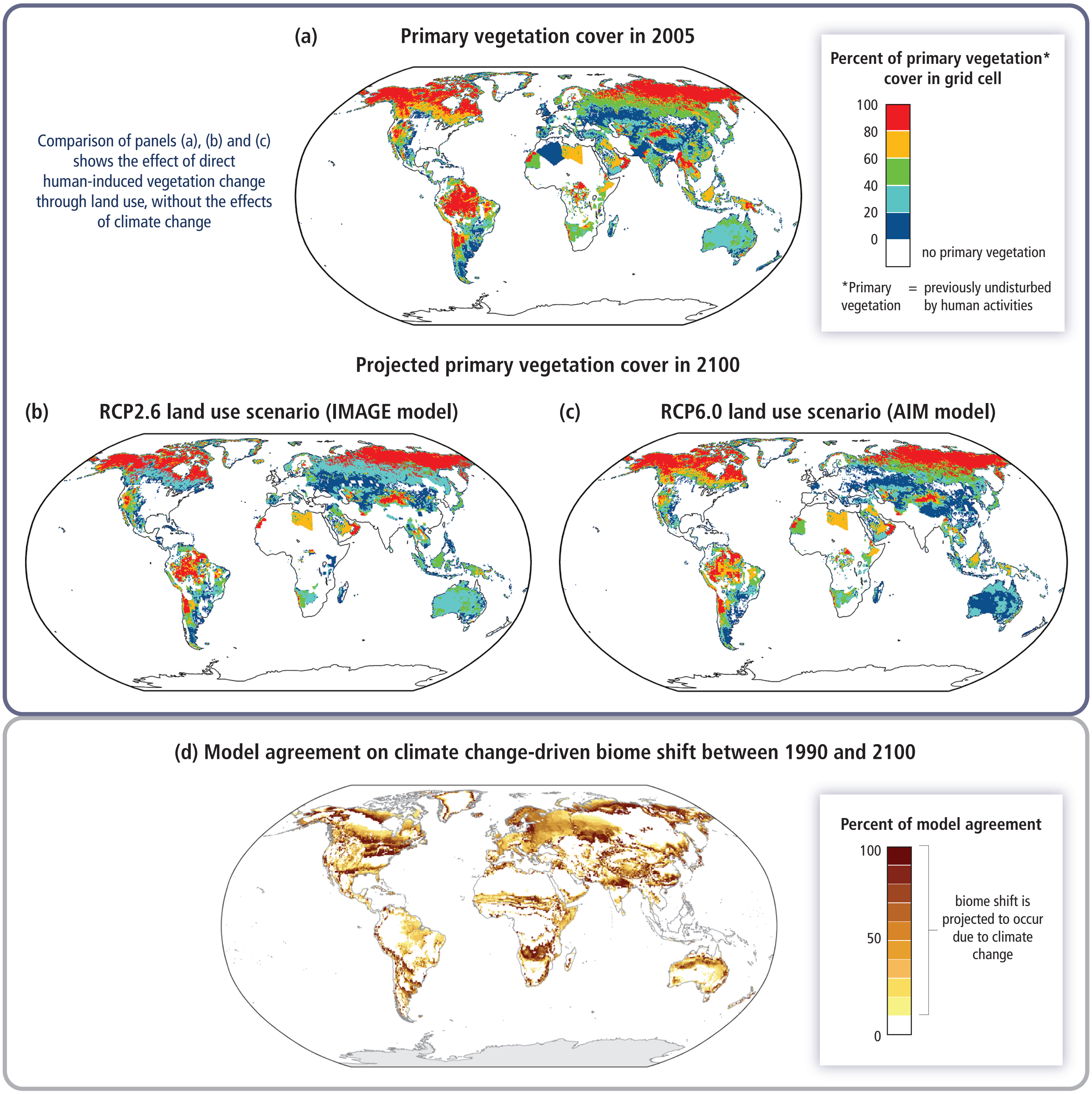

Figure 4-2 | Projections of climate change-driven biome shifts in the context of direct human land use. (a) Fraction of land covered by primary vegetation in 2005 (Hurtt et al., 2011); (b) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario, with no effect of climate change (Hurtt et al., 2011); (c) Fraction of land covered by primary vegetation in 2100 under the RCP6.0 land use scenario, with no effect of climate change (Hurtt et al., 2011). (d) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs, each forced by the SRES A2, A1B, and B1 scenarios; Gonzalez et al., 2010); Comparison of colored areas in (d) with those in (a) shows where climate-driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (c) with (a) illustrates two scenarios of how primary vegetation could change due to direct human land use, irrespective of the effects of climate change. (b) shows the land use scenario associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (d) as a result of mitigation measures, some of which involved land use. (c) shows the land use scenario associated with RCP6.0, in which global climate change is projected to be larger than RCP2.6 so biome shifts similar to those in (d) may occur alongside the projected land use changes in (c). For example, climate change-driven biome shift is projected in many Arctic land areas (d) which are unaffected by direct human land use at the present day (a) and in the RCP2.6 and 6.0 land use scenarios (b, c), indicating that climate change is the dominant influence on Arctic land ecosystems in these scenarios. In contrast, in Borneo, none of the GCMs analysed by Gonzalez et al. (2010) project climate change-driven biome shift (d), and instead a reduction in primary vegetation cover occurs in the mitigation scenario RCP2.6 as a consequence of direct human land use (b). A smaller reduction occurs in RCP6.0. Land use is therefore projected to be the dominant driver of change in Borneo in these scenarios. In the boreal forest regions of North America, Europe, and north-west Asia, climate change-driven biome shift (d) is projected in regions already subject to some influence of present-day human land use (a), and increased land use leading to further reductions in primary vegetation occur in both RCP2.6 (b) and RCP6.0 (c). Hence in these boreal forest regions, both climate change and land use are projected to be drivers of ecosystem change in these scenarios. Further details of the RCP land use/cover scenarios are given in Box 4-1, Figure 4-3, and Table 4-2.

preindustrial in some continental-scale regions; see WGI AR5 Section 5.5.1) was the same order of magnitude as the warming the Earth has experienced over the 20th century. Ecological effects were small compared to periods with larger climate excursions, but even this small warming was characterized by frequent fires in drier parts of the Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin et al., 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Prentice et al., 1996), and large-scale migration of Boreal Forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, also clearly impacted inland water systems (e.g., Smol and Douglas, 2007a; Battarbee et al., 2009; Beilman et al., 2009). However, there are no exact analogs for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude, and spatial scale of climate and atmospheric carbon dioxide (CO_2) change projected for the 21st century and beyond (Jansen et al., 2007; Schulte et al., 2010; Wing and Currano, 2013; see WGI AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land use change, invasive species, pollution, and overexploitation of natural resources (Pereira et al., 2010). There is *high confidence* that these interactions will be important: the paleoecological record provides *medium confidence* (*medium evidence*, *high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in the past (Lorenzen et al., 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial vegetation to large paleoclimate change (Prentice et al., 1996, 2011; Salzmann et al., 2008). The same types of models predict large changes in species ranges, ecosystem function, and carbon storage when forced by 21st century climate change, although the future situation is complicated by land use and other factors absent in the paleoenvironmental case (Sitch et al., 2008; Cheaib et al., 2012; see WGI AR5 Section 6.4). Thus, the paleoecological record and models that have been tested against it provide a coherent message that biomes will alter their functioning and composition in response to changing and often novel future climates: they will move as species mixtures change (Section 4.3.2.5 has more specific information on projected migration rates), novel plant communities will emerge, and significant carbon stock changes will take place (Williams and Jackson, 2007; MacDonald, 2010; Prentice et al., 2011; Willis and MacDonald, 2011). The paleoecological record and models provide *high confidence* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2°C to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler et al., 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Mueller, A.D. et al., 2009; Watrin et al., 2009; Williams et al., 2009; Harrison and Goni, 2010). This record provides a critical opportunity for model evaluation that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Jackson et al., 2009; Marlon et al., 2009; Williams et al., 2009; Daniau et al., 2010; Dawson et al., 2011). The paleoecological record also highlights the importance of including the direct effects of changing atmospheric CO_2 levels in efforts to simulate future ecosystem functioning and plant species competition (Prentice et al., 2011; Woillez et al., 2011; Bond and Midgley, 2012; Claussen et al., 2013).

The paleoclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (see WGI AR5 Chapters 5, 8, and 12), but even these slower changes often drove surprisingly abrupt, nonlinear, regional-scale change in terrestrial and inland water systems (e.g., Harrison and Goni, 2010; Williams et al., 2011), as did even slower climate change during the most recent Holocene interglacial (e.g., Booth et al., 2005; Kropelin et al., 2008; Williams, J.W. et al., 2010; Williams et al., 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for the global-scale rapid changes listed at the start of this section. State-of-the-art climate and Earth System Models (ESMs) are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011). Thus there is *high confidence* that these models may not capture some aspects of future abrupt climate change and associated ecosystem impacts (Leadley et al., 2010).

Frequently Asked Questions

FAQ 4.1 | How do land use and land cover changes cause changes in climate?

Land use change affects the local as well as the global climate. Different forms of land cover and land use can cause warming or cooling and changes in rainfall, depending on where they occur in the world, what the preceding land cover was, and how the land is now managed. Vegetation cover, species composition, and land management practices (such as harvesting, burning, fertilizing, grazing, or cultivation) influence the emission or absorption of greenhouse gases. The brightness of the land cover affects the fraction of solar radiation that is reflected back into the sky, instead of being absorbed, thus warming the air immediately above the surface. Vegetation and land use patterns also influence water use and evapotranspiration, which alter local climate conditions. Effective land use strategies can also help to mitigate climate change.

4.2.4. Multiple Stressors Interacting with Climate Change

The climatic and non-climatic drivers of ecosystem change need to be distinguished if the joint and separate attribution of changes to their causes is to be performed (see Chapter 18). In this section we elaborate on factors affecting ecosystems, operating simultaneously with climate change. These factors share underlining drivers with one another and with climate change to varying degrees; together they form a syndrome known as "global change." The individual effects of climate change, habitat loss and fragmentation, chemical pollution, overharvesting, and invasive alien species are increasingly well documented (Millennium Ecosystem Assessment, 2005c; Settele et al., 2010a) but much less is known about their combined consequences. Ecosystem changes may occur in cascades, where a change in one factor precipitates increased vulnerability with respect to other factors (Wookey et al., 2009) or propagates through the ecosystem as a result of species interactions (Gilman et al., 2010). Multiple stressors can act in a non-additive way (Shaw et al., 2002; Settele et al., 2010b; Larsen et al., 2011), potentially invalidating findings and interventions based on single-factor analysis. For instance, Larsen et al. (2011) demonstrated that non-additive interactions among the climate factors in a multifactor experiment were frequent and most often antagonistic, leading to smaller effects than predicted from the sum of single factor effects. Leuzinger et al. (2011) and Dieleman et al. (2012) have synthesized multifactor experiments and demonstrated that, in general, the effect size is reduced when more factors are involved, but Leuzinger et al. (2011) suggest that multifactor models tend to show the opposite tendency.

4.2.4.1. Land Use and Cover Change

Land use and cover change (LUCC) is both a cause (WGI AR5 Section 6.1.2) and a consequence of climate change. It is the major driver of current ecosystem and biodiversity change (Millennium Ecosystem Assessment, 2005b) and a key cause of changes in freshwater systems (Section 4.3.3.3). In tropical and subtropical areas of Asia, Africa, Oceania, and South America, the dominant contemporary changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures, industrial logging, and commercial plantations, followed by conversion of savannas, grasslands, and pastures to annual agriculture (Hosonuma et al., 2012; Macedo et al., 2012). In Europe there is net conversion of agricultural lands to forest (Rounsevell and Reay, 2009; Miyake et al., 2012). Conversion of peatlands to agriculture has been an important source of carbon to the atmosphere in Southeast Asia (Limpens et al., 2008; Hooijer et al., 2010; see Section 4.3.3.3).

Contemporary drivers of LUCC include rising demand for food, fiber, and bioenergy and changes in lifestyle and technologies (Hosonuma et al., 2012; Macedo et al., 2012). By mid-century climate change is projected to become a major driver of land cover change (Leadley et al., 2010). Non-climate environmental changes such as nitrogen deposition, air pollution, and altered disturbance regimes are also implicated in LUCC. Some of the underlying drivers of LUCC are also direct or indirect drivers of climate change (Cui and Graf, 2009; McAlpine et al., 2009; Mishra et al., 2010; Schwaiger and Bird, 2010; van der Molen et al., 2011; Groisman et al., 2012); this cause-and-effect entanglement of climate change and LUCC can confound the detection of climate change and make attribution to one or the other difficult. Local-to-regional climate change was at least partly attributed to LUCC in 11 of 26 studies reviewed for this chapter, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Cui and Graf, 2009; Li et al., 2009; McAlpine et al., 2009; Zhang et al., 2009; Fall et al., 2010; Jin et al., 2010; Mishra et al., 2010; Schwaiger and Bird, 2010; Wu et al., 2010; Carmo et al., 2012; Groisman et al., 2012. No climate effects studied: Suarez et al., 1999; Saurral et al., 2008; Tseng and Chen, 2008; Wang et al., 2008; Cochrane and Barber, 2009; Jia, B. et al., 2009; Rounsevell and Reay, 2009; Graiprab et al., 2010; Martin et al., 2010; Wiley et al., 2010; Clavero et al., 2011; Dai et al., 2011; Gao and Liu, 2011; Viglizzo et al., 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC (and land use itself) contributes to changes in the climate through altering the GHG concentrations in the atmosphere, surface and cloud albedos, surface energy balance, wind profiles, and evapotranspiration, among other mechanisms. The phrase "biophysical effects" is shorthand for the effect vegetation has on the climate other than through its role as a source or sink of GHGs. These effects are now well documented, significant, and are increasingly included in models of global and regional climate change. The GHG and biophysical effects of vegetation can be opposite in sign (de Noblet-Ducoudre et al., 2012) and operate at different scales. For instance, conversion of forest to non-forest generally releases CO_2 from biomass and soils to the atmosphere (causing warming globally), but may result in an increase in seasonally averaged albedo (local and global cooling, Davin et al., 2007) and a decrease in transpiration (local, but not global warming). Findell et al. (2007) concluded on the basis of model studies that the non-GHG climate impacts of LUCC were generally minor, but nevertheless significant in some regions. Brovkin et al. (2013), projecting the overall effect of LUCC on climate change for the 21st century, found LUCC to be a small driver globally, but locally important. Most global climate models suggest local average cooling effects following forest conversion to croplands and pastures (Pitman et al., 2009; Longobardi et al., 2012). Satellite observations suggest that the effect of conversion of the Brazilian savannas (*cerrado*) to pasture was to induce a local warming that was partly reversed when the pasture was subsequently converted to sugarcane (Loarie et al., 2011). Several modeling studies suggest that the global surface air temperature response to deforestation depends on the latitude at which deforestation occurs. High-latitude deforestation results in global cooling, low-latitude deforestation causes global warming, and the mid-latitude response is mixed (Bathiany et al., 2010; Davin and de Noblet-Ducoudre, 2010; van der Molen et al., 2011; Longobardi et al., 2012), with some exceptions documented for boreal forests (Spracklen et al., 2008). Boreal and tropical forests influence the climate for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation, especially in relation to a snowy background; Levis, 2010; Mishra et al., 2010; Longobardi et al., 2012) and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire et al., 2011; Pielke et al., 2011). The implications of these findings for afforestation as a climate mitigation action are discussed in Section 4.3.4.5. Forests may also influence regional precipitation through biophysical effects (Butt et al., 2011; Pielke et al., 2011; see Section 4.3.3).

In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to GHG-mediated effects,

Box 4-1 | Future Land Use Changes

Assessment of climate change effects on terrestrial and inland freshwater ecosystems requires the simultaneous consideration of land use and cover change (LUCC). The world is undergoing important shifts in land use, driven by accelerating demand for food, feed, fiber, and fuel. The main underlying driver is the rate at which per capita consumption is growing, particularly in emerging economies (Tilman et al., 2011). Policy shifts in developed countries favoring biofuel production have also contributed (Searchinger et al., 2008; Lapola et al., 2010; Miyake et al., 2012). Agricultural commodity prices have risen and may stay high through 2020 (OECD and FAO, 2010), owing to (1) demand growth outpacing supply growth, exacerbated by climate-related crop failure (Lobell et al., 2011); (2) decline in the rate of improvement in agricultural productivity (Ray et al., 2012); (3) shortage of arable land not already under cultivation, especially in the temperate zone; (4) growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa (Lambin and Meyfroidt, 2011); and (5) declining area under cultivation in temperate zones, mainly in developed countries. The shortage of arable land in temperate systems could put pressure on marginal or sensitive landscapes, mainly in Latin America's *cerrados* and grasslands (Brazil, Argentina) and in African savannas (Sudan, Democratic Republic of Congo, Mozambique, Tanzania, Madagascar) (Lambin and Meyfroidt, 2011).

Deforestation in developing countries correlates with the export of agricultural commodities (DeFries et al., 2010). Future LUCC remains uncertain, as it depends on economic trends and policies themselves dependent on complex political and social processes, including climate policy. By 2012, the deforestation rate in the Brazilian Amazon had declined by 77% below its 1996–2005 average (Nepstad et al., 2009; INPE, 2013) as a result of policy and market signals (Soares-Filho et al., 2010). This single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad et al., 2013).

Table 4-2 | Summary of drivers and outcomes of Land Use and Land Cover Change (LUCC) scenarios associated with Representative Concentration Pathways (RCPs; Hurtt et al., 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5, and 2.6 W m^{-2}) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), AIM (Asia-Pacific Integrated Model), GCAM (Global Change Assessment Model), and IMAGE (Integrated Model to Assess the Global Environment); see Hurtt et al. (2011) for further details).

RCP	Model and references	Key assumptions/drivers	Land use/cover outcomes
8.5	MESSAGE; Riahi et al. (2007)	• No climate change mitigation actions; radiative forcing still rising at 2100. • Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100). • Yield improvements and intensification assumed to account for most of production increases.	• Increase in cultivated land by about 305 million ha from 2000 to 2100. • Forest cover declines by 450 million ha from 2000 to 2100. • Arable land use in developed countries slightly decreased — all of the net increases occur in developing countries.
6.0	AIM; Fujino et al. (2006), Hijioka et al. (2008)	• Mitigation actions taken late in the century to stabilize radiative forcing at 6 W m^{-2} after 2100. • Population growth and economic growth. • Increasing food demand drives cropland expansion .	• Urban land use increases. • Cropland area expands. • Grassland area declines. • Total forested area extent remains constant.
4.5	GCAM; Smith and Wigley (2006), Wise et al. (2009)	• Mitigation stabilizes radiative forcing at 4.5 W m^{-2} before 2100. • Assumes that global greenhouse gas emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions are charged an equal penalty price, so reductions in land use change carbon emissions available as mitigation. • Food demand is met through crop yield improvements, dietary shifts, production efficiency, and international trade.	• Preservation of large stocks of terrestrial carbon in forests. • Overall expansion in forested area. • Agricultural land declines slightly due to afforestation.
2.6	IMAGE; van Vuuren et al. (2006), van Vuuren et al. (2007)	• Overall trends in land use and land cover are determined mainly by demand, trade, and production of agricultural products and bioenergy. • Expansion of croplands largely due to bioenergy production. • Production of animal products is met through shift from extensive to more intensive animal husbandry.	• Much agriculture relocates from high-income to low-income regions. • Increase in bioenergy production, new area for bioenergy crops near current agricultural areas. • Pasture largely constant.

Continued next page →

Box 4-1 (continued)

Each of the four main Representative Concentration Pathways (RCPs) used for future climate projections has a spatially explicit future land use scenario consistent with both the emissions scenario and the underlying associated socioeconomic scenario simulated by integrated assessment models, as well as conditions in 2005 (Hurtt et al., 2011; see also Table 4-2, Figure 4-2, Figure 4-3). In scenarios where cropland and pasture are projected to decrease, they are replaced with secondary vegetation. Tropical and boreal forest regions are both projected to undergo declining primary forest cover in most RCPs, but in RCP6.0 total forest area remains approximately constant and in RCP4.5 total forest area expands because of increased secondary forest. The extent to which primary vegetation is replaced by secondary vegetation, crops, or pasture varies between the RCPs (Figure 4-3), with no simple linear relationship between the extent of vegetation change and the level of total radiative forcing. Larger reductions in primary vegetation cover are projected in RCP8.5, owing to a general absence of proactive measures to control land cover change in that scenario. Large reductions are also projected in RCP2.6 owing to widespread conversion of land to biofuel crops (Figure 4-2). Smaller reductions are foreseen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest and afforestation as mitigation measures.

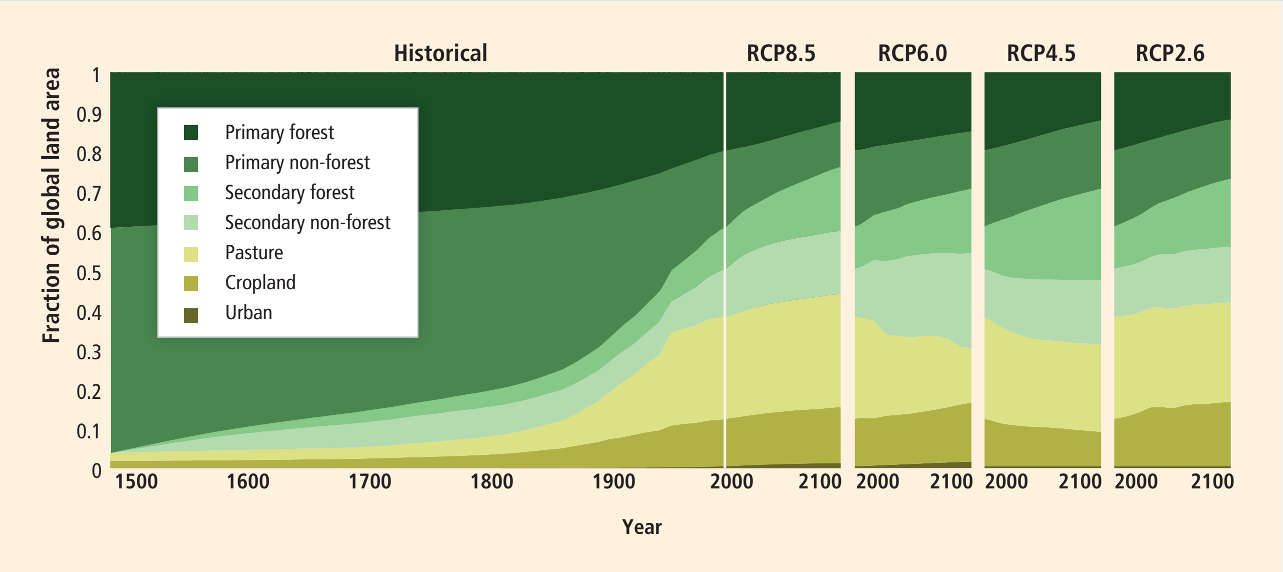

Figure 4-3 | Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture, and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk et al., 2010, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt et al., 2011).

which can materially alter the net outcome of the land cover change on the global climate (*high confidence*).

4.2.4.2. Nitrogen Deposition

The global nitrogen cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Canfield et al., 2010). Activities such as fertilizer production and fossil fuel burning currently transform 210 TgN yr^{-1} of nitrogen gas in the atmosphere into reactive forms of nitrogen (N_r) that can be readily used by plants and microorganisms in land and in the ocean, slightly more than the non-anthropogenic transformation of 203 TgN yr^{-1} (Fowler et al., 2013). Most of the transformations of anthropogenic N_r are on land (Fowler et al., 2013). The human-caused flow from land to oceans in rivers is 40 to 70 TgN yr^{-1}, additional to the estimated natural flux of 30 TgN yr^{-1} (Galloway et al., 2008; Fowler et al., 2013). Many of the sources of additional nitrogen share root causes with changes in the carbon cycle, such as increased use of fossil fuels and expansion and intensification of global agriculture. Nitrogen deposition, CO_2 concentrations, and temperatures are therefore increasing together at global scales (Steffen et al., 2011). Regional trends in nitrogen fluxes differ substantially: nitrogen fertilizer use and nitrogen deposition are stable or declining in some regions, such as Western Europe; but nitrogen deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in the tropics (Galloway et al., 2008) owing to increased needs for food and energy for growing populations in emerging economies (e.g., Zhu et al., 2005).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant species richness at nitrogen deposition loads exceeding between 5 and 20 kgN ha^{-1} yr^{-1} (Power et al., 2006; Clark and Tilman, 2008; Bobbink et al., 2010; but see Stevens, C.J. et al., 2010). Nitrogen deposition is currently above these limits in much of Europe, eastern North America, and southern Asia (Galloway et al., 2008), including in many protected areas (Bleeker et al., 2011).

The impacts of nitrogen deposition are often first manifested in freshwater ecosystems because they collect and concentrate the excess nitrogen (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either nitrogen and phosphorus limited or both (Elser et al., 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high-quality water, recreational amenity, and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of nitrogen and phosphorus is widespread in the lakes of the Northern Hemisphere (NH; Bergström and Jansson, 2006), although reduced nitrogen loading including deposition was observed between 1988 and 2003 in Sweden (Weyhenmeyer et al., 2007). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser et al., 2009).

Since the AR4, an increasing number of studies have models, observations, and experiments to understand and predict the interactive effects of nitrogen deposition, climate change, and CO_2 on ecosystem function. Interactions between nitrogen and other global change factors are widespread, strong, and complex (Rustad, 2008; Thompson et al., 2008; Langley and Megonigal, 2010; Gaudnik et al., 2011; Eisenhauer et al., 2012; Hoover et al., 2012; but see Zavaleta et al., 2003, for evidence of additive effects). In a study of plant-pollinator relationships, the combination of nitrogen deposition, CO_2 enrichment, and warming resulted in larger negative impacts on pollinator populations than could be predicted from the individual effects (Hoover et al., 2012). In a perennial grassland species, nitrogen limitation constrained the response to rising CO_2 (Reich et al., 2006). Broadly, the overall body of research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Churkina et al., 2010; Norby and Zak, 2011).

In forests in many parts of the world, experiments, observations, and models suggest that the observed increase in productivity and carbon storage is due to combinations of nitrogen deposition, climate change, fertilization effects of rising CO_2, and forest management (Huang et al., 2007; Magnani et al., 2007; Pan et al., 2009; Churkina et al., 2010; Bellassen et al., 2011; Bontemps et al., 2011; de Vries and Posch, 2011; Eastaugh et al., 2011; Norby and Zak, 2011; Shanin et al., 2011; Lu et al., 2012). N deposition and rising CO_2 appear to have generally dominated in much of the NH. However, the direct effects of rising temperature and changes in precipitation may exceed nitrogen and CO_2 as key drivers of ecosystem primary productivity in a few decades time. In grasslands, however, experiments show that plant productivity is increased more by nitrogen addition (within the projected range for this century) than by elevated CO_2, also within its projected range, and that nitrogen effects increase with increasing precipitation (Lee et al., 2010).

In contrast to forests and temperate grasslands, nitrogen deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens et al., 2011). The interactions between nitrogen deposition and climate change remain difficult to understand and predict (Menge and Field, 2007; Ma et al., 2011), in part owing to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled carbon, nitrogen, and phosphorus cycles (Menge and Field, 2007; Niboyet et al., 2011).

Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that nitrogen deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the 21st century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due to expansion of agricultural lands (Alkemade et al., 2009). Models that explicitly take into account interactive effects of climate change and nitrogen deposition on plant communities project that nitrogen deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid et al., 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to the Earth's surface) has risen over the past 150 years from a global average of 20 to 30 ppb to 30 to 50 ppb, with high spatial and temporal variability (Horowitz, 2006; Oltmans et al., 2006; Cooper et al., 2010; WGI AR5 Figure 2.7). This is due to (1) increasing anthropogenic emissions of gases that react in the atmosphere to form ozone (Denman et al., 2007) and (2) the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone precursor gases are volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). Intercontinental transport of these precursors contributes to rising global background ozone concentrations, including in regions where local ozone precursor emissions are decreasing (Dentener et al., 2010). Global sources of VOC are predominantly biogenic (BVOC), especially forests (Hoyle et al., 2011).

Negative effects of the current levels of ozone have been widely documented (Mills et al., 2011). A meta-analysis of more than 300 articles addressing the effect of ozone on tree growth (Wittig et al., 2009)—focused largely on NH temperate and boreal species—concluded that current levels of tropospheric ozone suppress growth by 7% relative to preindustrial levels. Modeling studies that extrapolate experimentally measured dose-response relationships suggest a 14 to 23% contemporary reduction in Gross Primary Productivity (GPP) worldwide, with higher values in some regions (Sitch et al., 2007) and 1 to 16% reduction of Net Primary Productivity (NPP) in temperate forests (Ainsworth et al., 2012).

The mechanisms by which ozone (O_3) affects plant growth are now better known (Hayes et al., 2007; Ainsworth et al., 2012). Chronic exposure to O_3 at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008), although in some cases ozone exposure increases stomatal conductance (Wilkinson and Davies, 2010). For the species studied,

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carbon assimilation rates and leaf area are generally reduced, while respiration increases and leaf senescence is accelerated—all leading to a reduction in NPP. Conifers are less sensitive than broad-leafed species. In a modeling study, lower stomatal conductance due to O_3 exposure increased river runoff by reducing the loss of soil moisture through transpiration, but observational studies that measured runoff in relation to ozone exposure show divergent trends on this issue (McLaughlin et al., 2007; Wittig et al., 2007; Mills et al., 2009; Huntingford et al., 2011).

A modeling study (Sitch et al., 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17 to 31% of the projected increase in global carbon storage due to increasing CO_2 concentrations over the 21st century, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance, widely observed under elevated CO_2, should help protect plants from ozone damage. Some chamber experiments (Bernacchi et al., 2006) and model studies (Klingberg et al., 2011) suggest this to be the case. The one plot-scale study of CO_2 and O_3 interactions in a temperate forest (Karnosky et al., 2005; Hofmockel et al., 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in plant sensitivity to O_3 (Ainsworth et al., 2012). Other than changing cultivars or species, few management actions promoting adaptation to higher levels of O_3 are currently available (Wilkinson and Davies, 2010; Teixiera et al., 2011). Research into developing ozone resistant varieties and chemical protectants against damage may provide management options in the future (Wilkinson and Davies, 2010; Ainsworth et al., 2012).

4.2.4.4. Rising Carbon Dioxide

Rising atmospheric CO_2 concentrations affect ecosystems directly and through biological and chemical processes. The consequences for the global carbon cycle are discussed in WGI AR5 Box 6.3; the discussion here focusses on impacts on terrestrial and inland water systems. Paleo records over the Late Quaternary (past Myr) show that changes in the atmospheric CO_2 content between 180 and 280 ppmv had ecosystem-scale effects worldwide (Prentice and Harrison, 2009).

In contrast to the oceans, changes in CO_2 concentrations in inland waters are influenced primarily by biological processes, such as inputs of terrestrial organic matter, particularly dissolved organic carbon (DOC), and bacterial respiration (van de Waal et al., 2010; Aufdenkampe et al., 2011). Carbon can, however, become limiting during intense algal blooms, especially in the surface waters of stratified lakes and reservoirs, and rising atmospheric CO_2 concentrations may stimulate higher algal production under these conditions (van de Waal et al., 2010). Higher CO_2 concentrations can lead to increases in the C:N and C:P ratios of phytoplankton, though the trophic consequences of this are difficult to predict because zooplankton may alter their feeding behavior to select higher quality forms of algae or increase feeding rate (Urabe et al., 2003; van de Waal et al., 2010).

Over the past 2 decades, and especially since AR4, experimental investigation of elevated CO_2 effects on plants and ecosystems has used mainly Free Air CO_2 Enrichment (FACE) techniques (Leakey et al., 2009). FACE is considered more realistic than earlier approaches using enclosed chambers, because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. Plants with a C_3 photosynthetic system, which includes most species but excludes warm-region grasses, show an increase in photosynthesis under elevated CO_2, the precise magnitude of which varies between species. Acclimation ("down-regulation") occurs under long-term exposure, leading to cessation of effects in some (Norby and Zak, 2011) but not all studies (Leakey et al., 2009). The C_4 photosynthetic system found in most tropical grasses and some important crops is not directly affected by elevated CO_2, but C_4 plant productivity generally increases under elevated CO_2 because of increased water use efficiency (WUE). Transpiration is decreased under elevated CO_2 in many species, due to reduced opening of stomatal apertures, leading to greater WUE (Leakey et al., 2009; Leuzinger and Körner, 2010; De Kauwe et al., 2013). Increasing WUE is corroborated by studies of stable carbon isotopes (Barbosa et al., 2010; Koehler et al., 2010; Silva et al., 2010; Maseyk et al., 2011). The WUE increase does not acclimate to higher CO_2 in the medium term, that is, over several years (Leakey et al., 2009). Satellite observations from 1982–2010 show an 11% increase in green foliage cover in warm, arid environments (where WUE is most important) after correcting for the effects of precipitation variability (Donohue et al., 2013); gas exchange theory predicts 5 to 10% greening resulting from rising CO_2 over this period.

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition, and biodiversity loss) on ecosystem function are extremely complex. Generally, nitrogen use efficiency is

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Frequently Asked Questions

FAQ 4.2 | What are the non–greenhouse gas effects of rising carbon dioxide on ecosystems?

Carbon dioxide (CO_2) is an essential building block of the process of photosynthesis. Simply put, plants use sunlight and water to convert CO_2 into energy. Higher CO_2 concentrations enhance photosynthesis and growth (up to a point), and reduce the water used by the plant. This means that water remains longer in the soil or recharges rivers and aquifers. These effects are mostly beneficial; however, high CO_2 also has negative effects, in addition to causing global warming. High CO_2 levels cause the nitrogen content of forest vegetation to decline and can increase their chemical defenses, reducing their quality as a source of food for plant-eating animals. Furthermore, rising CO_2 causes ocean waters to become acidic (see FAQ 6.3), and can stimulate more intense algal blooms in lakes and reservoirs.

increased under higher CO_2 (Leakey et al., 2009) although, in some tree FACE experiments, productivity increases as a result of enhanced CO_2 if sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi et al., 2007). In one 10-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness expected from nitrogen addition (Reich, 2009), whereas no such benefit was reported for an alpine grassland in France (Bloor et al., 2010) or a Danish heathland ecosystem (Kongstad et al., 2012).

Elevated CO_2 can affect plant response to other stresses, such as high temperature (Lloyd and Farquhar, 2008) and drought. Ozone exposure decreases with lower stomatal conductance (Sitch et al., 2007). In savannas, faster growth rates under higher CO_2 can allow woody plants to grow tall enough between successive fires to escape the flames (Bond and Midgley, 2001; Scheiter and Higgins, 2009). Differential species responses to elevated CO_2 appear to be altering competition (Dawes et al., 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Mohan et al., 2006; Potvin et al., 2007; Lewis et al., 2009a).

Experimental studies have shown that elevated CO_2 leads to increased leaf C:N ratios in woody plants, forbs, and C_3 grasses (but not C_4 grasses), which may decrease their quality as food and increase herbivorous insect feeding rates and changes to their density and community structure (Sardans et al., 2012). Plants may also become more toxic to herbivores under elevated CO_2 levels, through increased concentrations of carbon- and nitrogen-based defenses (Lindroth, 2010; Cavagnaro et al., 2011).

Our understanding of ecosystem responses to elevated CO_2 is incomplete in some respects. The majority of FACE experiments apply upper CO_2 concentrations of approximately 550 ppmv, which is below the concentrations projected by 2100 under higher emissions scenarios. The physiology of photosynthesis suggests that direct CO_2 effects saturate at levels of approximately 700 ppmv (Long et al., 2004). Most elevated CO_2 experiments impose a sudden increase of CO_2 concentration as opposed to the gradual rise experienced in reality. Most large-scale FACE experiments have been conducted in temperate locations (e.g., Hickler et al., 2008); there are currently no large-scale tropical or boreal FACE experiments. The magnitude of CO_2 effects decreases as the spatial scale of study increases (Leuzinger et al., 2011).The scale of controlled experiments is limited to approximately 100 m^2. Extrapolation to larger scales ignores large-scale atmospheric feedbacks (Körner et al., 2007) and catchment-scale hydrological effects (see Box CC-VW). Overall, there is *medium confidence* (*much evidence*, *medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate.

CO_2 effects are a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change (Sitch et al., 2008; Lapola et al., 2009; Friend et al., 2013).The direct effect of CO_2 on plant physiology, independent of its role as a GHG, means that assessing climate change impacts on ecosystems and hydrology solely in terms of global mean temperature rise (or equivalently, expressing GHG effects solely in terms of radiative forcing) is an oversimplification (Huntingford et al., 2011; Betts et al., 2012). A 2°C rise in global mean temperature, for example, may have a different net impact on ecosystems depending on the change in CO_2 concentration accompanying the rise (e.g., Good et al., 2011a). A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs.

4.2.4.5. Diffuse and Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and the proportions of direct versus diffuse radiation. In some regions, direct radiation has been reduced by up to 30 W m^{-2} over the industrial era, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are –3.3 and +0.9 W m^{-2}, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis because a smaller fraction of the vegetation canopy is light-saturated, making photosynthesis more light efficient at the canopy scale (Knohl and Baldocchi, 2008; Kanniah et al., 2012). In a global model that included this effect, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; however, under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st century (Mercado et al., 2009), All RCPs project decreased aerosol concentrations due to air quality protection measures, as already seen in some countries. The influence of the form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (see WGI AR5 Section 7.7), but this topic is at present insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g., Walther et al., 2009) and for particular areas, including mountain tops and polar regions (McDougall et al., 2011; Chown et al., 2012). Species invasions have increased over the last several decades (*very high confidence*), and the aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton et al., 2010; McGeoch et al., 2010; Simberloff et al., 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson et al., 2008; Bradley et al., 2009; Britton et al., 2010; Bellard et al., 2013). Although there is increasing evidence that some species invasions have been assisted by climate change, there is *low confidence* that species invasions have in general been assisted by recent climatic trends because of the overwhelming importance of human-facilitated dispersal in mediating invasions. The spread of alien species has several causes, including habitats made favorable by climate change (Walther et al., 2009), deliberate species

Frequently Asked Questions

FAQ 4.3 | Will the number of invasive alien species increase as a result of climate change?

Some invasive plants and insects have already been shown to benefit from climate change and will establish and spread into new regions (where they are "aliens"), once they are introduced. The number of newly arrived species and the abundance of some already established alien species will increase because climate change will improve conditions for them. At the same time, increasing movement of people and goods in the modern world, combined with land use changes worldwide, increases the likelihood that alien species are accidentally transported to new locations and become established there. There are many actions that can be taken to reduce, but not eliminate, the risk of alien species invasions, such as the treatment of ballast water in cargo ships and wood products, strict quarantine applied to crop and horticultural products, and embargos on the trade and deliberate introduction of known invader species. Some invasive species will suffer from climate change and are expected to decrease in range and population size in some regions. Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

transfer, and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread, and survival of invasive species populations (Dukes et al., 2009; Walther et al., 2009; Bradley et al., 2010; Huang et al., 2011; Chown et al., 2012). Some degree of climate/habitat match has been found to be a prerequisite of establishment success across seven major plant and animal groups (Hayes and Barry, 2008). A range of alien species responses and local consequences are expected (e.g., Rahel and Olden, 2008; Frelich et al., 2012; Haider et al., 2012; West et al., 2012). Invasive species, compared to native species, may have traits that favor their survival, reproduction, and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium* to *high confidence*; van Kleunen et al., 2010; Willis, C.G. et al., 2010; Buswell et al., 2011; Davidson et al., 2011; Zerebecki and Sorte, 2011; Haider et al., 2012; Matzek, 2012). Some invasive plants are more drought tolerant (Crous et al., 2012; Matzek, 2012; Perry et al., 2012), and on average they have higher overall metabolic rates, foliar nitrogen concentrations, and photosynthetic rates than their native counterparts (Leishman et al., 2007).

Extreme climate events provide opportunities for invasion by generating disturbances and redistributing available resources (Diez et al., 2012) and changing connectivity between different ecosystems. Current warming has already enabled many invasive alien species, including plant, vertebrate, invertebrate, and single-cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther et al., 2009; Smith et al., 2012). However, population declines and range contractions are predicted for some invasive species in parts of their ranges (Bradley et al., 2009; Sobek-Swant et al., 2012; Taylor et al., 2012; Bertelsmeier et al., 2013). The expansion of invasive species in some areas and contraction in others will contribute to community reorganization and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Britton et al., 2010; Kiesecker, 2011; Martinez, 2012; see also Section 4.3.2.5). For example, invasive grasses may be favored over native ones with increasing temperatures (Parker-Allie et al., 2009; Chuine et al., 2012; Sandel and Dangremond, 2012).

In a few cases, benefits to biodiversity and society may result from the interactive effects of climate change and invasive species, such as increases in resources available to some threatened species (Caldow et al., 2007), forest structural recovery (Bolte and Degen, 2010), and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific and may be either positive or negative (Williams, A.L. et al., 2007). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010; but see Section 4.2.4.4).The effectiveness of invasive alien species management for sequestering carbon is uncertain and context specific (Peltzer et al., 2010). Longer term, indirect effects of invasive alien species will be more important than direct, short-term effects, for instance, as a result of changes in soil carbon stocks and tree community composition (*low* to *medium confidence*; Peltzer et al., 2010).

Synergistic interactions occur between climate change and invasive alien species, along with landscape change, habitat disturbance, and human-facilitated breakdown of dispersal barriers (Brook et al., 2008; Angeler and Goedkoop, 2010; Bradley et al., 2010; Winder, M. et al., 2011). Climate change and invasive alien plant species generally increase the risk and intensity of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions, and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties, and water demand (*medium confidence*; Schnitzler et al., 2007; Rahel and Olden, 2008; Britton et al., 2010).

A range of climate change-related variables (extreme events and changes in precipitation, temperature, and CO_2) will continue to exacerbate the establishment and spread of pests, vectors, and pathogens and negatively impact production systems (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has contributed to the spread of many invasive insect species, such as the mountain pine bark beetle, and resulted in forest destruction (*high confidence*; Raffa et al., 2008). The interactions between crop growth, climate change, and pest or pathogen dynamics are difficult to predict (West et al., 2012). Management strategies may become less effective as a consequence of the decoupling of biocontrol relationships and less effective mechanical control as biomass and/or population size of invasive species increases (*low* to *medium confidence*; Hellmann et al., 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Change

The vulnerability of ecosystems to climate change, that is, their propensity to be adversely affected, is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system (including its coupled social elements) can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. Tolerance and adaptability both interact with exposure, which in the case of terrestrial and freshwater ecosystems means the magnitude and rate of climate change relative to ranges of climatic conditions and rates of change under which the ecosystem developed and its organisms evolved. Chapter 19 provides a full discussion on vulnerability concepts.

4.3.1. Changes in the Disturbance Regime

The species composition at a given location is determined by three considerations: the ability of species to reach the location; the physiological tolerance of the species in relation to the range of conditions experienced there; and interactions with other species, including competitors, symbionts, predators, prey, and pathogens. Occasional disturbances relieve competition, create opportunities for the establishment and success of less dominant species, and may facilitate dispersal. Moderate disturbance is thus important in maintaining diversity and ecosystem function (Connell, 1978). Exposure to disturbances keeps tolerance of disturbance in the population high. Fire, floods, and strong winds are all examples of biodiversity-sustaining climate disturbances, provided that their frequency and intensity do not deviate greatly above or below the regime to which the species are adapted. Average environmental conditions may be less of a determinant of species range and abundance than the extreme conditions, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration (Zimmermann et al., 2009). The projected changes in probability of extremes are typically disproportionately larger than the projected changes in the mean (see IPCC, 2012; but also Diffenbaugh et al., 2005). Biotic disturbances, such as pest and pathogen outbreaks are also often implicated in ecosystem change, and may be enabled by climate change.

It is suggested that ecosystem regime shifts resulting from climate change (alone or in interaction with other factors) will often be triggered by changes in the disturbance regime, rather than by physiological tolerance for the mean conditions (Thonicke et al., 2001). A "disturbance regime" refers to the totality of different types of disturbance events in a system, each characterized by its probability of occurrence, intensity, and other relevant attributes, such as its seasonal pattern. A corollary is that disturbance-related change is abrupt rather than gradual. Change in the fire disturbance regime is emerging as a key proximal mechanism and early indicator of terrestrial ecosystem change (Girardin et al., 2009; Johnstone et al., 2010). Changes in the fire regime have in some cases been attributed to climate change (Littell et al., 2009). Regional trends in fire occurrence have been observed since 2000 (Giglio et al., 2013), but interpreting their significance requires a longer term perspective (e.g., Bergeron et al., 2010).

4.3.2. Observed and Projected Change in Ecosystems

This section highlights key observed changes in terrestrial and freshwater ecosystems over the recent past, as well as changes projected during the 21st century. For observations, we assess the degree of confidence that change has been detected, and separately the confidence we have in attributing the change to climate change (Figure 4-4). Confidence in detection is considered to be *very high* when there is *high agreement* between many independent studies, species, ecosystems, or regions and where there is *robust evidence* that the changes over time are statistically significant (see Chapter 18; Mastrandrea et al., 2010). Note that a slightly different definition of detection is used here than in Chapter 18, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate-related variation. Confidence in attribution to climate change is *very high* when three tests are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; the time series of observations is sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. In the sections that provide the details of the assessment of detection and attribution, estimated levels of confidence are given even in cases where the capacity for detection or attribution capacity is *low* or *very low*, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. In all cases the estimates of confidence levels are based on global and cross-taxon assessments, so the positioning may be different for specific taxa or regions. Some of the sections include assessments of model-based projections of future change; the confidence assessment of detection and attribution does not extend to these.

A key message arising from the analysis of *detection* and *attribution* is that climate impacts on the functioning of organisms and ecosystems are clearest when temperature is a principal driver, changes are relatively rapid, and confounding factors play a small role. At one end of the spectrum, the large warming signal over the last several decades in much of the Arctic tundra combined with minimal human impacts is associated with *high confidence* in detection of an increase in shrubs and permafrost thawing and *high confidence* in the attribution to climate warming (Section 4.3.3.1.1). Likewise, the phenology of most organisms is sensitive to temperature, confounding effects are often small, and the response is rapid, leading to *high confidence* in detection and attribution of changes in phenology to warming (Section 4.3.2.1). At the opposite end of the spectrum, species extinctions are very difficult to attribute to climate change (Section 4.3.2.5), in part because other factors dominate recent extinctions. This does not mean that climate has not played an important contributing role; indeed it has been argued that the low level of confidence in attribution is due to the lack of studies looking for climate signals in extinctions (Cahill et al., 2013). Similarly there is

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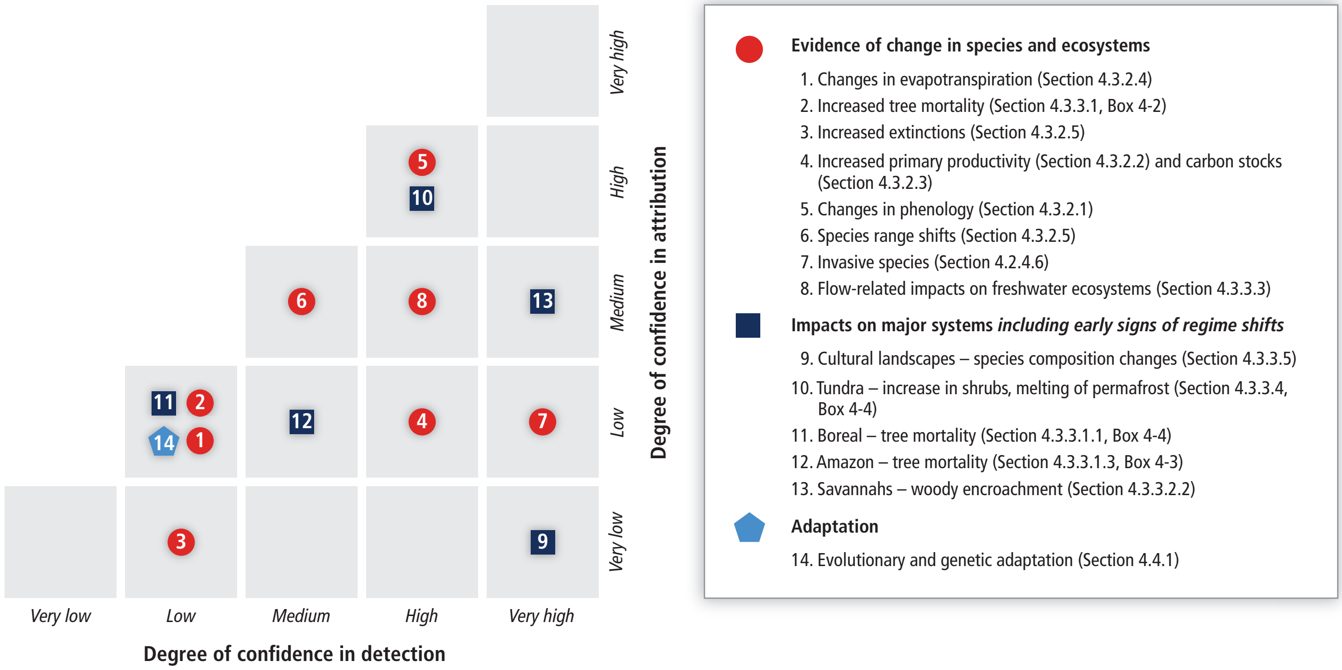

Figure 4-4 | Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea et al., 2010), attribution criteria outlined in Chapter 18, and detection criteria defined in the text. The symbols in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions. Details of the assessments that were used in positioning each of the points can be found in the sections given in parentheses.

very good evidence that species composition is changing in cultural landscapes, but the important role of other factors, for example, land management and nitrogen deposition, makes attribution of a contribution to recent warming difficult. This analysis indicates that responses in most species and ecosystem levels will become more apparent over time because (1) observed organism-level changes will have long-term impacts on ecosystem functioning (*high confidence*; Sections 4.3.2.1, 4.3.2.5, 4.3.3) and (2) warming signals can be detected in ecosystems where the recent warming has been strong and confounding factors are minimal. In addition, the absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century in medium to high scenarios (all but RCP2.6); ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (Jones et al., 2009).

4.3.2.1. Phenology

Further evidence from ground-based and satellite studies, focused mainly on the NH (Northern Hemisphere), supports the AR4 conclusion that shifts in phenology have occurred over recent decades. "Spring advancement"—earlier occurrence of spring events, such as breeding, bud burst, breaking hibernation, flowering, migration—is seen in hundreds of plant and animal species in many regions (Menzel et al., 2006; Cleland et al., 2007; Parmesan, 2007; Primack et al., 2009; Cook et al., 2012a; Peñuelas et al., 2013), although magnitudes of change vary considerably and some species show no change (Parmesan, 2007). Apparent discrepancies between two estimates of overall NH spring advancement noted in AR4 (-2.3 days per decade, Parmesan and Yohe, 2003; -5.1 days per decade, Root et al., 2003) are largely resolved when methodological differences are accounted for, particularly the inclusion of species that do not show phenological changes (Parmesan, 2007). A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007).

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4.3.2.1.1. Plants

Spring advancement is seen across the NH including North America (e.g., Cook et al., 2008, 2012b), Europe (e.g., Menzel et al., 2006; Cook et al., 2012b), Asia (e.g., Primack et al., 2009; Ma and Zhou, 2012), and the High Arctic (Høye et al., 2007). Changes are generally larger at higher latitudes. A meta-analysis indicates mean NH spring advancement of -1.1 ± 0.16 days per decade for herbs and grasses (85 species), -1.1 ± 0.68 days per decade for shrubs (6 species), and -3.3 ± 0.87 days per decade for trees (16 species), over a record period of 35 to 132 years, depending on the study. The warming trends detected in the well-mixed surface waters (epilimnion) of many lakes in North America, Eurasia, and Africa (Adrian et al., 2009) are associated with the earlier onset of spring phytoplankton blooms (Winder and Schindler, 2004; Winder and Sommer, 2012). Satellite data also indicate a general tendency of spring advancement, though there is variation between satellite studies, especially at local scales, due to the use of different instruments and methods (e.g., White et al., 2009). A study using the Advanced Very High Resolution Radiometer (AVHRR) suggests that for vegetation between 30°N and 80°N, the start of the growing season advanced by -5.2 days between 1999 and 1982 and advanced a further -0.2 days by 2008; while the growing season end was delayed by 6.6 days between 1982 and 2008 (Jeong et al., 2011). Studies with a more recent satellite instrument, the Moderate Resolution Imaging Spectrometer (MODIS), also show spring advancement (e.g., Ahl et al., 2006). The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

4.3.2.1.2. Animals

Many new studies provide further evidence of changes in animal phenology (e.g., amphibians: Kusano and Inoue, 2008; Phillimore et al., 2010; birds: Pulido, 2007; Thorup et al., 2007; mammals: Adamik and Kral, 2008; Lane et al., 2012; insects: Robinet and Roques, 2010; freshwater plankton: Adrian et al., 2009). Changes in breeding phenology are reported from various regions and different taxa (e.g., Parmesan, 2006, 2007; Post et al., 2008; Primack et al., 2009). In the NH several studies show advancements of egg laying dates in birds (e.g., Parmesan, 2007: -3.7 ± 0.7 days per decade, in 41 species). In contrast, a delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 was seen for two of nine seabirds in the Eastern Antarctic, linked to decreased sea ice extent (Barbraud and Weimerskirch, 2006). Spring arrival dates have advanced for many migratory birds (e.g., Thorup et al., 2007). Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g., Sokolov, 2006; Adamik and Pietruszkova, 2008).

A large body of evidence therefore shows that, in NH temperate, boreal, and Arctic regions, spring advancement has occurred in many plant and animal species over the last several decades (*high confidence* due to *robust evidence* but only *medium agreement* when examined across all species and regions; Figure 4-4).

Understanding of the drivers of phenological change has also improved further since AR4. Many observational studies find a correlation with higher temperatures (Cook et al., 2012a). Experimental manipulation generally supports this (e.g., plants: Cleland et al., 2012; bird egg-laying: Visser et al., 2009; insects: Musolin et al., 2010; Kollberg et al., 2013). Some individual studies find good agreement between experimental warming and *in situ* observations (e.g., Gunderson et al., 2012) although a meta-analysis suggests that experiments can substantially under-predict advances in the timing of flowering and leafing of plants in comparison with observational studies (Wolkovich et al., 2012). Observational data can also be affected by methodological issues; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux et al., 2011). Rates of warming across a season may also be important (Schaper et al., 2012). Models can be used to explain relationships between observed phenological changes and environmental variables. For example, a model based on water temperature captured the observed temporal and spatial variation in *Daphnia* phenology in NH lakes (Straile et al., 2012). Other environmental factors related to temperature, such as timing of snowmelt, snow cover, and snow depth, can play a role. Snowmelt changes led to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye et al., 2007) and earlier flowering in an alpine plant in the Rocky Mountains, USA, between 1975 and 2008 (Hülber et al., 2010; Lambert et al., 2010). Earlier snowmelts decreased floral resources and hence affected insect population dynamics in mountain ranges in the USA in the years 1980, 1985, 1986, and 1989 (Boggs and Inouye, 2012). In Colorado, USA, the yellow-bellied marmot emerged earlier from hibernation due to snowmelts becoming earlier over 1976–2008 (Ozgul et al., 2010) while in Alberta, Canada, Columbian ground squirrels emerged later over 1992–2012 owing to delayed snowmelts associated with increased late-season snowstorms (Lane et al., 2012). Delayed emergence from hibernation was associated with decreased population growth rate (Lane et al., 2012). Food availability can be important; for example, in the Yukon area, Canada, the date of giving birth in North American squirrels (*Tamiascurus hudsonicus*) advanced by an average of -18 days over the period 1989–1998, coinciding with increasing abundance of white spruce cones, their major food source (Réale et al., 2003).

Phenological response can differ with migration strategy in birds, for example short-distance migrants show greater advancements in spring arrivals than long distant migrants (e.g., Saino et al., 2009; but see Parmesan, 2006 for different patterns). In a temperate region (Massachusetts, USA), declining sizes of populations and migrating cohorts of North American Passerine birds account for a large part of the variation in migration times between 1970 and 2002 (Miller-Rushing et al., 2008). The remaining variation was explained by climatic variables, migration distance, and date. The variation in bird migration phenology change can also be related to differing patterns of feather changes during moulting times, food availability at stop-over places, and differing health conditions of individual species (Gordo, 2007).

Although a number of non-climatic influences on phenology are also identified, an increased number of observational and experimental studies, across many organism types, suggest that warming has contributed to the overall spring advancement observed in the NH (*high confidence* due to *high agreement* and *medium evidence*).

4.3.2.2. Primary Productivity

Primary production, the process of plant growth, is fundamental to the global carbon cycle (see Section 4.3.2.3) and underpins provisioning ecosystem services such as food, timber, and grazing. Trends in the amount, seasonal timing, variability, location, and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation, and observation all agree that primary production is directly sensitive to most aspects of climate change, is indirectly affected via the effects of climate on pests and diseases, and is responsive to many of the other changes simultaneously taking place in the world, such as described in Section 4.2.4. The diverse and frequently nonlinear form of responses to the factors influencing primary production, combined with the complexity of interactions between them, means that at a given location the net outcome can be an increase, no change, or a decrease in productivity.

The concentration of CO_2 in the atmosphere shows clear patterns in space and time largely related to the primary productivity of the land and oceans. The contribution by terrestrial ecosystems to these patterns can be estimated using isotope measurements, emission databases, and models (Canadell et al., 2007). It consists of a sink term, due to increased net ecosystem production, plus a source term due to land use change. During the decade 2000–2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the estimated preindustrial level, leading to a land sink of 2.6 + 1.2 PgC yr^{-1} (these values are from WGI AR5 Section 6.3.2.6; the uncertainty range is 2 standard deviations; for the primary literature see also Raupach et al., 2008; Le Quéré et al., 2009). The net uptake of carbon by the land is highly variable year to year, mainly in response to climate variation and major volcanic eruptions (Peylin et al., 2005; Sitch et al., 2008; Mercado et al., 2009). Given the uncertainty range, it is not possible to conclude whether the rate of carbon uptake by the residual land sink has increased or decreased over the past 2 decades (Raupach et al., 2008; WGI AR5 Section 6.3.2.6). Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections, using the RCP scenarios, suggest that the rate of net carbon uptake by terrestrial ecosystems will decrease during the 21st century except under the RCP4.5 scenario, and by the greatest amount under RCP8.5. There is greater uncertainty between models than between scenarios; in some models terrestrial ecosystems become a net source of CO_2 to the atmosphere (WGI AR5 Section 6.4.3.2, especially Figure 6.26).

It is possible to downscale the land sink estimate continentally, using inversion modeling techniques and the growing network of precision atmospheric observations. There is *high agreement* and *medium evidence* that the net land uptake in natural and semi-natural terrestrial ecosystems is broadly distributed around the world, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land use change, principally deforestation (Pan et al., 2011).

The observed trends in Normalized Difference Vegetation Index (NDVI), a satellite proxy for primary productivity, are discussed under various ecosystem-specific discussions above and below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, or simply reflect inadequacies in the indicator, method of analysis, and length of the record in relation to the high interannual variability. AR4 reported a trend of increasing seasonally accumulated NDVI ("greening") at high northern latitudes (Fischlin et al., 2007; based on Sitch et al., 2007), but subsequent observations show a lower rate and no geographical uniformity (Goetz et al., 2007). More than 25% of high-latitude North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000 (Goetz et al., 2007). NDVI trend analyses in rangelands show varying patterns around the world, with substantial disagreement between studies (Millennium Ecosystem Assessment, 2005a; Bai et al., 2008; Beck, H.E. et al., 2011; Fensholt et al., 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid-1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees, or herbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Prince et al., 2007; Hellden and Tottrup, 2008; Seaquist et al., 2009). In the period 2000–2009 no NDVI trend was apparent in the Sahel (Samanta et al., 2011).

Tree rings record changes in tree growth over approximately the past millennium. Many tree ring records show accelerated tree growth during much of the 20th century (Briffa et al., 2008), which often correlates with rising temperature. Variations in tree ring width, density, and isotopic composition arise from many factors, including temperature, moisture stress, CO_2 fertilization, N deposition, and O_3 damage, but also stand structure and management. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s, a number of tree ring records show a decline in tree growth (Wilson et al., 2007). Several possible causes have been suggested for this, including increasing water stress and O_3 damage; but the most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010), so tree ring-based conclusions for the past 2 decades are based on a relatively small body of evidence and may therefore be biased. Recent tree ring studies were often specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010) and may therefore not be representative of global tree growth. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in Section 4.3.2.3) are an alternate data source for recent decades.

Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti et al., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O'Reilly et al., 2003). In both cases the changes were attributed by the authors to climate change.

In summary, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution (Figure 4-4).

4.3.2.3. Biomass and Carbon Stocks

The forest biomass carbon stock can be estimated from the routine forest monitoring that takes place for management and research purposes. Forest inventories were generally designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well developed for NH temperate and boreal forest (Nabuurs et al., 2010; Ryan et al., 2010; Wang, B. et al., 2010). Data for tropical and Southern Hemisphere forests and woodlands also exist (Maniatis et al., 2011; Tomppo et al., 2010) but are typically less available and comprehensive (Romijn et al., 2012). More and better data may become available as a result of advances in remote sensing (e.g., Baccini et al., 2012) and increased investment in forest monitoring through initiatives such as the Reduced Emissions from Deforestation and Degradation (REDD) of the United Nations Framework Convention on Climate Change (UNFCCC).

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais et al., 2008; Luyssaert et al., 2010) and the USA

(Birdsey et al., 2006). Canadian managed forests increased in biomass only slightly during 1998–2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Phillips et al., 2009) forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005. Globally, for the period 2000–2007, recently undisturbed forests are estimated to have withdrawn 2.30 ± 0.49 PgC yr^{-1} from the atmosphere, while formerly cleared tropical forests, now regrowing, withdrew an additional 1.72 ± 0.54 PgC yr^{-1} (Pan et al., 2011). The global terrestrial carbon sink is partly offset by the losses of forest carbon stocks to the atmosphere through land use change, largely in the tropics, of 1.1 ± 0.8 PgC yr^{-1} (2000–2009, WGI AR5 Section 6.3.2.6).

The carbon stock in global soils, including litter and peatlands is 1500 to 2400 PgC, with permanently frozen soils adding another 1700 PgC (Davidson and Janssens, 2006). The soil carbon stock is thus more than 10 times greater than the carbon stock in forest biomass (Kindermann et al., 2008). Changes in the size of the soil carbon stock result from changes in the net balance of inputs and losses over a period of many years. Inputs derive from primary production, discussed in Section 4.3.2.2, and are mostly modestly increasing under climate change. Losses result principally through the respiration of soil microbes, which increases with increasing temperature. The present and future temperature sensitivity of microbial respiration remains uncertain (Davidson and Janssens, 2006). An analysis of long-term respiration measurements from the soil around the world suggests that it has increased over the past 2 decades by an amount of 0.1 PgC yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). If soil respiration were to exceed terrestrial net primary production globally and on a sustained basis, the present net terrestrial sink would become a net source, accelerating the rate of CO_2 build-up in the atmosphere (Luo, 2007).

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The carbon stock in freshwater systems is also quite high in global terms. Annual rates of storage (0.03 to 0.07 PgC yr^{-1}) may be trivial compared with sequestration by soils and terrestrial vegetation, but lake sediments are preserved over longer time scales (+10 kyr compared with decades to centuries), and Holocene storage of carbon in lake sediments has been estimated at 820 Pg (Cole et al., 2007). Manmade impoundments represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr^{-1} (Cole et al., 2007).

A short-duration study of the temperature sensitivity of decomposition in flooded coastal soils, extrapolated to the 21st century, suggested that increases in respiration would exceed increases in future production (Kirwan and Blum, 2011). Further detail on wetland soil carbon stocks can be found in Section 4.3.3.3 on peatlands and on permafrost carbon stocks in Box 4-4 and in Chapter 28.

In summary, biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century (Figure 4-4). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation, and land management make attribution of these trends to climate change difficult (*low confidence*).

4.3.2.4. Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET) includes evaporation from the ground and vegetation surfaces, and transpiration through plant stomata. Both are affected by multiple factors (Luo et al., 2008) including temperature, solar (shortwave) and thermal (longwave) radiation, humidity, soil moisture, and terrestrial water storage; transpiration is additionally affected by CO_2 concentration through its influence on plant stomatal conductance. Studies using lysimeters, evaporation pans, the balance of observed precipitation and runoff, and model reconstructions indicate both increases and decreases in ET in different regions and between approximately 1950 and the present (Huntington, 2008; Teuling et al., 2009; Douville et al., 2013). Flux tower records have at most 15 years duration (FLUXNET, 2012), so there are insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations or simulated with models constrained by observations. Estimates of ET from 1120 globally (but non-uniformly) distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.75 mm yr^{-2} (Wang, K. et al., 2010). Other studies, using data-constrained models, indicated global ET rises of between 0.25 and 1.1 mm yr^{-2} during the 1980s and 1990s (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly linked with increased surface solar radiation and thermal radiation (Wild et al., 2008) or warming (Jung et al., 2010). There has been no significant ET trend since approximately 2000 (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly due to soil moisture limitation (Jung et al., 2010). Overall, there is *low confidence* in both detection and attribution of long-term trends in ET (Figure 4-4).

Experiments show that rising CO_2 decreases transpiration and increases intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance; Leakey et al., 2009). Some modeling studies suggest that, over the 20th century, the effects of CO_2 on decreasing transpiration are of comparable size but opposite to the effects of rising temperature (Gerten et al., 2008; Peng et al., 2013). However, the observed general increase in ET argues that reduced transpiration cannot be the dominant factor (Huntington, 2008). A meta-analysis of studies at 47 sites across five ecosystem types (Peñuelas et al., 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since preindustrial times (1850 or before) has also been found at several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and also in a temperate semi-natural grassland since 1857 (Koehler et al., 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen et al., 2011).

4.3.2.5. Changes in Species Range, Abundance, and Extinction

Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavorable and into favorable climates; or by going locally or globally extinct (Dawson et al., 2011; Bellard et al., 2012; Peñuelas et al., 2013; see also Section 4.2.3). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied

Frequently Asked Questions

FAQ 4.4 | How does climate change contribute to species extinction?

There is a consensus that climate change over the coming century will increase the risk of extinction for many species. When a species becomes extinct, a unique and irreplaceable life form is lost. Even local extinctions can impair the healthy functioning of ecosystems.

Under the fastest rates and largest amounts of projected climate change, many species will be unable to move fast enough to track suitable environments, which will greatly reduce their chances of survival. Under the lowest projected rates and amounts of climate change, and with the assistance of effective conservation actions, the large majority of species will be able to adapt to new climates, or move to places that improve their chances of survival. Loss of habitat and the presence of barriers to species movement increase the risk of extinctions as a result of climate change.

Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these recent extinctions is the subject of considerable debate.

by large reductions in abundance (see Section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions, and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for diseases (Zarnetske et al., 2012). Global extinctions result in the permanent loss of unique forms of life.

Substantial evidence has accumulated since AR4 reinforcing the conclusion that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner, with species abundances increasing in areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution to climate change of recent global species extinctions, and in projections of future extinctions, have become more apparent since the AR4.

4.3.2.5.1. Observed species range shifts

The number of studies looking at observed range shifts and the breadth of species examined have greatly increased since AR4. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin et al., 2007; Chen et al., 2011) is a useful simplification of species responses; however, responses to warming are conditioned by changes in precipitation, land use, species interactions, and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation, and land use often result in range shifts that are downhill or away from the poles (Rowe et al., 2010; Crimmins et al., 2011; Hockey et al., 2011; McCain and Colwell, 2011; Rubidge et al., 2011; Pauli et al., 2012; Tingley et al., 2012; Zhu et al., 2012). There are large differences in the ability of species groups (i.e., broad taxonomic categories of species) and species within these groups to track changes in climate through range shifts (Angert et al., 2011; Mattila et al., 2011; Chen et al., 2011). For example, butterflies appear to be able track climate better than birds (community shifts: Devictor et al., 2012; but see Chen et al., 2011 for range shifts) while some plants appear to be lagging far behind climate trends except in mountainous areas (Bertrand et al., 2011; Doxford and Freckleton, 2012; Gottfried et al., 2012; Zhu et al., 2012; Telwala et al., 2013). There is growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen et al., 2011; Brommer et al., 2012; Sunday et al., 2012) and difficulties in detecting local extinction with confidence (Thomas et al., 2006).

Rising water temperatures are also implicated in species range shifts in river fish communities (e.g., Comte and Grenouillet, 2013), combined with a decrease in recruitment and survival as well as range contraction of cold-water species such as salmonids (Bartholow, 2005; Bryant, 2009; Ficke et al., 2007; Jonsson and Jonsson, 2009; Hague et al., 2011). Shifts in freshwater fish species range toward higher elevation and upstream (Hickling et al., 2006; Comte and Grenouillet, 2013) also are not keeping pace with the rate of warming in streams and rivers. While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist et al., 2006) and cool- and warm-water species of fish (Tisseuil et al., 2012), there is *high confidence* that range contraction threatens the long-term persistence of some fully aquatic species.

Rates of recent climate change have varied greatly across the globe, ranging from rapid warming to cooling (Burrows et al., 2011; Dobrowski et al., 2013). Taking this spatial variation into account should enhance the ability to detect climate-related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured only in the regions where the range shifts were observed

(Chen et al., 2011), providing greater confidence in attribution of the range shifts to climate change. Average range shifts across taxa and regions in this study were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. However, this approach remains a simplification, as the climate drivers of species range changes, for example, temperature and precipitation, have frequently shifted in different geographical directions (Dobrowski et al., 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley et al., 2012). Overall, studies since AR4 show that species range changes result from interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope, that leads to *high confidence* that several well-studied species groups, such as insects and birds, have shifted their ranges over significant distances (tens of kilometers or more) over the last several decades, and that these range shifts can be attributed to changes in climate. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in detection and attribution when examined across all species and all regions.

4.3.2.5.2. Future range shifts

Projections of climate change impacts on future species range shifts since the AR4 have been dominated by studies using Ecological Niche Models (ENMs) that project future ranges based on correlative models of current relationships between environmental factors and species distribution (Peterson et al., 2011). A variety of process-based models are starting to be more widely used to make projections of future species distributions (Buckley et al., 2010; Beale and Lennon, 2012; Cheaib et al., 2012; Higgins et al., 2012; Foden et al., 2013). Model comparisons show that correlative models generally predict larger range shifts than process-based models for trees (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). For other species groups that have been studied, differences in projections between model types show no clear tendency (Kearney et al., 2009; Buckley et al., 2010; Bateman et al., 2012). There has been some progress in model validation: projected species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see Section 4.2.2 and above in this section), but further validation is needed (Green et al., 2008; Pearman et al., 2008; Nogues-Bravo et al., 2010; Dawson et al., 2011). Modeling studies typically do not account for a number of key mechanisms mediating range shifts, such as genetic adaptation and phenotypic plasticity (see Section 4.4.1.2), species interactions, or human-mediated effects. An important limitation in most studies is that realistic species displacement rates are not accounted for (i.e., rates at which species are able to shift their ranges through dispersal and establishment); as such, they only indicate changes in the location of favorable and unfavorable climates, from which potential shifts in species distribution can be inferred, but not rates of change (Bateman et al., 2013).

Analyses and models developed since AR4 permit the estimation of the ability of a wide range of species to track climate change. Figure 4-5 provides a synthesis of the projected abilities of several species groups to track climate change. This analysis is based on (1) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie et al., 2009; Burrows et al., 2011; Chen et al., 2011; Sandel et al., 2011; Feeley and Rehm, 2012; Dobrowski et al., 2013); and (2) species displacement rates across landscapes for a broad range of species (e.g., Stevens, V.M. et al., 2010; Nathan et al., 2011; Barbet-Massin et al., 2012; Kappes and Haase, 2012; Meier et al., 2012; Schloss et al., 2012; see additional references in Figure 4-5 legend). Comparisons of these rates indicate whether species are projected to be able to track climate as it changes. When species displacement capacity exceeds climate velocity it is inferred that species will be able to keep pace with climate change; when displacement capacity is lower than projected climate velocities then they will not, within the bounds of uncertainty of both parameters. This simplified analysis is coherent with more sophisticated model analyses of climate-induced species displacement across landscapes, some of which have evaluated additional constraints such as demographics, habitat fragmentation, or competition (e.g., Meier et al., 2012; Schloss et al., 2012).

Rates of climate change over the 20th century and projected for the 21st century are shown in Figure 4-5a. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections under a wide range of GHG emissions scenarios (i.e., WGI AR5 Chapter 12; Knutti and Sedláček, 2012). Rates of global warming for land surfaces have averaged approximately 0.03°C yr^{-1} since 1980, but have slowed over the last decade and a half (WGI AR5 Chapter 2). At the low end of projected future rates of warming, rates decrease over time, reaching near zero by the end of the century (RCP2.6). At the high end, projected rates increase over time, exceeding 0.06°C yr^{-1} by the end of the century (RCP8.5), and perhaps above 0.08°C yr^{-1} at the upper bound.

Climate velocity is defined as the rate of change in climate over time (e.g., °C yr^{-1}, if only temperature is considered) divided by the rate of change in climate over distance (e.g., °C km^{-1}, if only temperature is considered) and therefore depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-5b; Loarie et al., 2009; Dobrowski et al., 2013). For example, climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large (e.g., Rocky Mountains, Andes, Alps, Himalayas; Figure 4-5b, leftmost axis). Climate velocity for temperature is generally high in flat areas because the rate of change in temperature over distance is low (e.g., parts of the USA Midwest, Amazon basin, West Africa, central Australia; Figure 4-5b, rightmost axis). In flat areas, climate velocity can exceed 8 km yr^{-1} for the highest rates of projected climate change (RCP8.5). We have focused on climate velocity for temperature change, but several analyses also account for precipitation change.

Rates of displacement vary greatly within and among species groups (Figure 4-5c). Some species groups, notably herbaceous plants and trees, generally have very low displacement capacity. Other species groups such as butterflies, birds (not shown), and large vertebrates generally have a very high capacity to disperse across landscapes, nonetheless

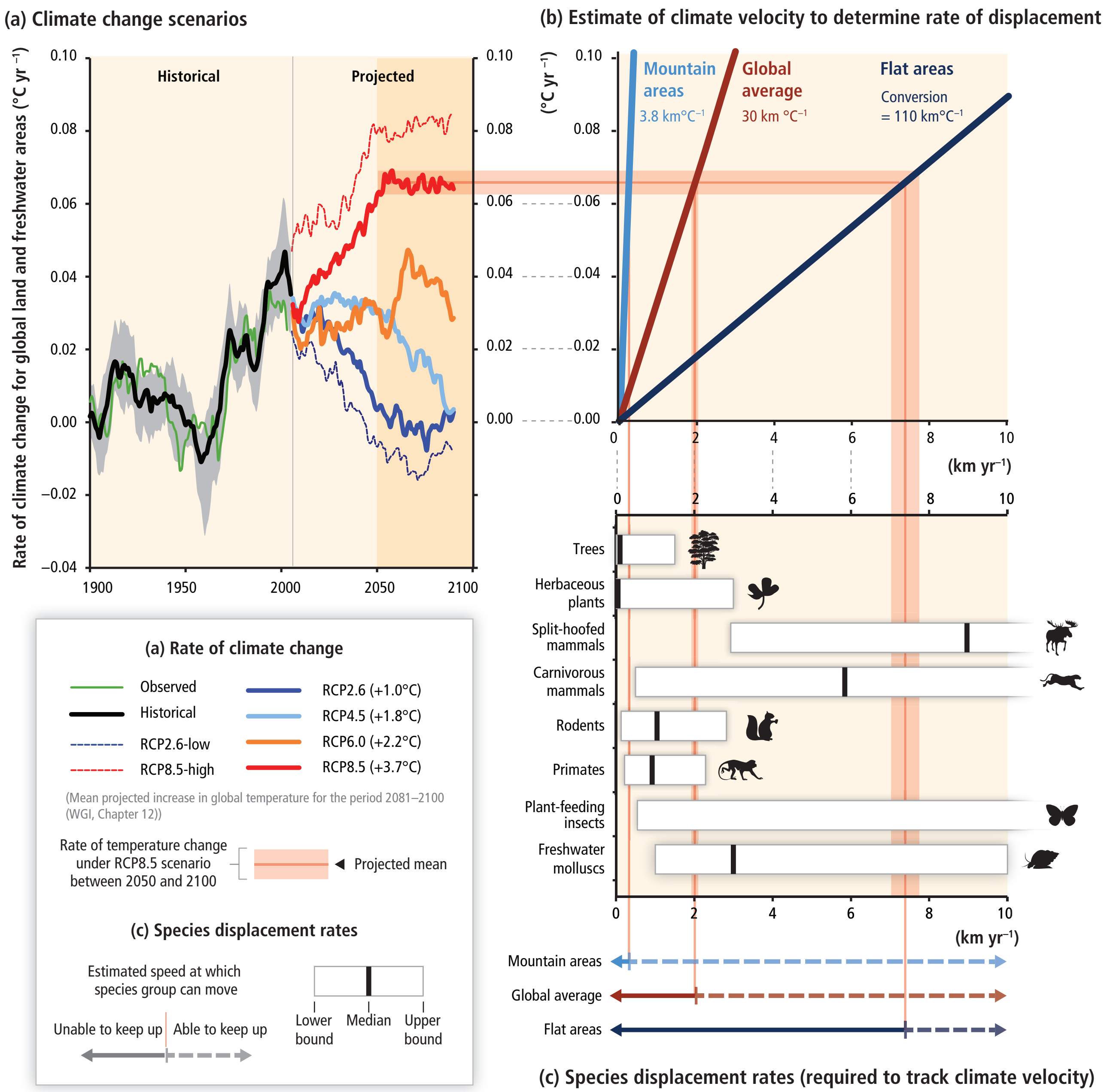


Figure 4-5 | (a) Rates of climate change, (b) corresponding climate velocities, and (c) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in (a) to the points of intersection with the three climate velocity scalars in (b). Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in (c). Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (a) Observed rates of climate change for global land areas are derived from Climatic Research Unit/Hadley Centre gridded land-surface air temperature version 4 (CRUTEM4) climate data reanalysis; all other rates are calculated based on the average of Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles for the historical period (gray shading indicates model uncertainty) and for the future based on the four Representative Concentration Pathway (RCP) emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (b) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity (historical: Burrows et al., 2011; Chen et al., 2011; Dobrowski et al., 2013; projected future: Loarie et al., 2009; Sandel et al., 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (center), and large flat regions (right). (c) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = approximately 95% of observations or models for herbaceous plants, trees, and plant-feeding insects or median ± 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates, and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark et al., 2003; Kinlan and Gaines, 2003; McLachlan et al., 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins et al., 2003; Iverson et al., 2004; Epstein et al., 2007; Goetz et al., 2011; Nathan et al., 2011; Meier et al., 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modeled dispersal rates of a wide range of mammal species (mean of Schloss et al., 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini et al., 2013 and generation length by Pacifici et al., 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg et al., 2010; Chen et al., 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).

some species in these groups have low dispersal capacity. Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of tens to a few hundreds of meters per year. Overall, many plant species are foreseen to be able to track climates only in mountainous areas at medium to high rates of warming, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates generally have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities, in particular the Amazon basin, thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change (Schloss et al., 2012). On a global average, many rodents, as well as some carnivores and freshwater molluscs, are projected to be unable to track climate at very high rates of climate change (i.e., >0.06°C yr^{-1}). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see Section 4.3.2.5.1).

Humans can increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner et al., 2010). Human activities can also substantially reduce displacement rates. In particular, habitat loss and fragmentation typically reduces displacement rates, sometimes substantially (Eycott et al., 2012; Hodgson et al., 2012; Meier et al., 2012; Schloss et al., 2012). The degree to which habitat fragmentation slows displacement depends on many factors, including the spatial pattern of the fragments and corridors, maximum dispersal distances, population dynamics, and the suitability of intervening modified habitats as stepping-stones (Pearson and Dawson, 2003). Species and habitat dependencies may also speed or hinder species displacement. For example, host plants are projected to move much more slowly than most herbivorous insects, substantially slowing displacement of the insects if they are unable to switch host plants (Schweiger et al., 2012). Likewise, many habitats are structured by slow moving plants, so habitat shifts are projected to lag behind climate change (Hickler et al., 2012; Jones et al., 2012), which will in turn mediate the movements of habitat specialists.

There are significant uncertainties in climate velocities, measured estimates of dispersal and establishment rates, and model formulations. Climate velocities are calculated using a variety of methods and spatial resolutions, making direct comparisons difficult and leading to *low confidence* in estimates of climate velocities in Figure 4-5b (*limited evidence* and *medium agreement*). The lowest estimates of global average climate velocity (Figure 4-5b, center axis) are about half the best estimate values we show on the climate velocity axes (Loarie et al., 2009), while the highest estimates are about four times higher (Burrows et al., 2011), but high estimates may be artefacts of using very large spatial resolutions (Dobrowski et al., 2013). In addition, the climate velocities used in Figure 4-5 are based on temperature alone, and recent analyses indicate that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski et al., 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). There are often large differences in estimates of dispersal rates across methods due to intrinsic uncertainties in the methods and differences in the mechanisms included (Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins et al., 2003; Meier et al., 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated, leading to an overestimation of displacement rates. For trees there is *medium confidence* in projections of their displacement rates due to the large number of studies of past, current, and future displacement rates (*robust evidence* and *medium agreement*). Less is known for other broad species groups such as mammals, so there is only *low confidence* in estimates of their displacement capacity. Estimates for other groups, such as freshwater molluscs, are based on very little data, so estimates of their dispersal capacity are poorly constrained.

Despite large uncertainties in displacement capacity and climate velocity, the rates of displacement required to track the highest rates of climate change (RCP8.5) are so high that many species will be unable to do so (*high confidence*). Moderate rates of projected climate change (RCP4.5 and RCP6.0) would allow more species to track climate, but would still exceed the capacity of many species to track climate (*medium confidence*). The lowest rates of projected climate change (RCP2.6) would allow most species to track climate toward the end of the century (*high confidence*). This analysis highlights the importance of rates of climate change as an important component of climate change impacts on species and ecosystems. For example, differences in the magnitude of climate change between scenarios are small at mid-21st century (WGI AR5 Chapter 12), but the differences in rates of climate change are large. At mid-century, it is projected that species would need to move little at the lowest rates of climate change (RCP2.6), but will need to move approximately 70 km per decade in flat areas in order to track climate at the highest rates of climate change (RCP8.5).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and experience large range contractions (Warren et al., 2013), whereas displacement that keeps pace with climate change greatly increases the fraction of species that can maintain or increase their range size (Menéndez et al., 2008; Pateman et al., 2012). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-5b; Colwell et al., 2008; Engler et al., 2011; Gottfried et al., 2012; Pauli et al., 2012; but see Dullinger et al., 2012). However, species that already occur near mountaintops (or other boundaries) are among the most threatened by climate change because they cannot move upwards (Ponniah and Hughes, 2004; Thuiller et al., 2005; Raxworthy et al., 2008; Engler et al., 2011; Sauer et al., 2011). The consequences of losing favorable climate space are not yet well understood. The extent to which adaptive responses might allow persistence in areas of unfavorable climates is discussed in Section

4.4.1.2. In the absence of adaptation, losing favorable climate space is projected to lead to reduced fitness, declining abundance, and local extinction, with potentially large effects on biodiversity and ecosystem services (see evidence of early signs of this for trees in Box 4-2).

4.3.2.5.3. Observed changes in abundance and local extinctions

Observations of range shifts imply changes in abundance, that is, colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* for several species groups is reviewed here (Section 4.3.2.5), in AR4, and by Cahill et al. (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have also occurred in response to recent global warming (*high confidence*; Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fulop et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013). Confident attribution to recent global warming is hindered by confounding factors such as disease, land use change, and invasive species (Cahill et al., 2013). New tentative conclusions since AR4 are that climate-related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*; Cahill et al., 2013) and that precipitation can be a stronger driver of abundance change than temperature in many cases (Tian et al., 2011; Tingley et al., 2012). This gives weight to concerns that biological interactions, which are poorly known and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn et al., 2009; Bellard et al., 2012; Hannah, 2012; Urban et al., 2012; Vadadi-Fulop et al., 2012).

A few examples illustrate the types of change in abundance that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high-latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein et al., 2007; Goetz et al., 2011; Myers-Smith et al., 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*), have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill et al., 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin (*Aptenodytes forsteri*) population that has been attributed to regional changes in climate (Trathan et al., 2011). The attribution of these declines to changes in regional climate is well supported, but the link to global warming is tenuous (Barbraud et al., 2011).

Mountains also provide good examples of changes in abundance that can be linked to climate because very strong climate gradients are found there. AR4 highlighted these responses, and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli et al. (2012) reported an increase in species richness from plant communities of mountaintops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in southern Europe. An increase in the population size of warm-adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried et al., 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric N deposition, and forest management practices (Gottfried et al., 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see Section 4.3.2.5.5).

4.3.2.5.4. Projected changes in abundance and local extinction

Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. These models project that local extinction risk by the end of the 21st century due to climate change will vary widely, ranging from almost no increase in local extinction risk within the current range for some species or species groups to greatly increased risk of local extinctions in more than 95% of the present-day range for others (Settele et al., 2008; Bellard et al., 2012). Projected local colonization rates are equally variable. There has been progress in coupling species distribution models and species abundance models for a wide range of organisms (Keith et al., 2008; Midgley et al., 2010; Matthews et al., 2011; Schippers et al., 2011; Oliver et al., 2012a; Renwick et al., 2012). These hybrid approaches predict extinction risk directly, rather than by inference from changes in climate suitability (Fordham et al., 2012). The main conclusions from these studies are that changes in species abundance and local extinction risk as a result of climate change can range from highly positive to highly negative, and are determined by a combination of factors, including its environmental niche, demographics, and life history traits, as well as interactions among these factors (Aiello-Lammens et al., 2011; Clavero et al., 2011; Conlisk et al., 2012; Fordham et al., 2012; Swab et al., 2012).

Changes in abundances will also be accompanied by changes in genetic diversity (see also Section 4.4.1.2). At the intraspecific level, future climate change is projected to induce losses of genetic diversity when it results in range contraction (Balint et al., 2011; Pauls et al., 2013). In addition, there is theoretical and observational evidence this loss of genetic diversity will depend on rates of migration and range contraction (Arenas et al., 2012). In these cases, reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Climate change may also compound losses of genetic diversity that are already occurring due to other global changes such as the introduction of alien species or habitat fragmentation (Winter et al., 2009; see also Section 4.2.4.6).

4.3.2.5.5. Observed global extinctions

Global species extinctions, many of them caused by human activities, are now occurring at rates that approach or exceed the upper limits of observed natural rates of extinction in the fossil record (Barnosky et al., 2011). However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades (birds: Szabo et al., 2012; but see Kiesecker, 2011, for amphibians). Most extinctions over the last several centuries have been attributed to habitat loss, overexploitation, pollution, or invasive species, and these are the most important current drivers of extinctions (Millennium Ecosystem Assessment, 2005b; Hofmann and Todgham, 2010; Cahill et al., 2013). Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN), only 20 have been tenuously linked to recent climate change (Cahill et al., 2013; see also Hoffmann et al., 2010; Szabo et al., 2012). Molluscs, especially freshwater molluscs, have by far the highest rate of documented extinctions of all species groups (Barnosky et al., 2011). Mollusc extinctions are attributed primarily to invasive species, habitat modification, and pollution; changes in climate are rarely evoked as a driver (Lydeard et al., 2004; Regnier et al., 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill et al., 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have been attributed to changing climate, even tenuously (Burkhead, 2012; Cahill et al., 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds et al., 2006). There have been more than 160 probable extinctions of amphibians documented over the last 2 decades, many of them in Central America (Pounds et al., 2006; Kiesecker, 2011). The most notable cases have been the golden toad (*Bufo periglenes*) and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction previously ascribed to global warming with "very high confidence" (Pounds et al., 2006; Fischlin et al., 2007). This case has raised a number of important issues about attribution because (1) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor, and (2) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi et al., 2008; Lips et al., 2008; Anchukaitis and Evans, 2010; Bustamante et al., 2010; Collins, 2010; Vredenburg et al., 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). Owing to *low agreement* among studies there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change. While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Brook et al., 2008; Pereira et al., 2010; Hof et al., 2011b). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming, owing to the very low fraction of global extinctions that have been ascribed to climate change and tenuous nature of most attributions.

4.3.2.5.6 Projected future species extinctions

Projections of future extinctions due to climate change have received considerable attention since AR4. AR4 stated with *medium confidence* "that approximately 20–30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above preindustrial levels" (Fischlin et al., 2007). All model-based analyses since AR4 broadly confirm this concern, leading to *high confidence* that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century (Pereira et al., 2010; Sinervo et al., 2010; Pearson, 2011; Warren et al., 2011, 2012; Bellard et al., 2012; Hannah, 2012; Ihlow et al., 2012; Sekercioglu et al., 2012; Wearn et al., 2012; Foden et al., 2013). Most studies indicate that extinction risk rises rapidly with increasing levels of climate change, but some do not (Pereira et al., 2010). The limited number of studies that have directly compared land use and climate change drivers have concluded that projected land use change will continue to be a more important driver of extinction risk throughout the 21st century (Pereira et al., 2010). There is, however, broad agreement that land use, and habitat fragmentation in particular, will pose serious impediments to species adaptation to climate change as it is projected to reduce the capacity of many species to track climate (see Section 4.3.2.5.3). These considerations lead to the assessment that future species extinctions are a high risk because the consequences of climate change are potentially severe, widespread, and irreversible, as extinctions constitute the permanent loss of unique life forms.

There is, however, low agreement concerning the overall fraction of species at risk, the taxa and places most at risk, and the time scale for climate change-driven extinctions to occur. Part of this uncertainty arises from differences in extinction risks within and between modeling studies: this uncertainty has been evaluated in AR4 and subsequent syntheses (Pereira et al., 2010; Warren et al., 2011; Bellard et al., 2012; Cameron, 2012). All studies project increased extinction risk by the end of the 21st century due to climate change, but as indicated in AR4 the range of estimates is large. Recent syntheses indicate that model-based estimates of the fraction of species at substantially increased risk of extinction due to 21st century climate change range from below 1% to above 50% of species in the groups that have been studied (Pereira et al., 2010; Bellard et al., 2012; Cameron, 2012; Foden et al., 2013). Differences in modeling methods, species groups, and climate scenarios between studies make comparisons between estimates difficult (Pereira et al., 2010; Warren et al., 2011; Cameron, 2012).

Many papers published since AR4 argue that the uncertainty may be even higher than indicated in syntheses of model projections, due to limitations in the ability of current models to evaluate extinction risk (e.g., Kuussaari et al., 2009; Pereira et al., 2010; Dawson et al., 2011; McMahon et al., 2011; Pearson, 2011; Araujo and Peterson, 2012; Bellard et al., 2012; Fordham et al., 2012; Hannah, 2012; Kramer et al., 2012; Zurell et al., 2012; Halley et al., 2013; Moritz and Agudo, 2013). Models frequently do not account for genetic and phenotypic adaptive capacity, dispersal capacity, population dynamics, the effects of habitat fragmentation and loss, community interactions, micro-refugia, and the effects of rising CO_2 concentrations, all of which could play a major role in determining species vulnerability to climate change, causing models to either over- or underestimate risk. In addition, difficulties in model validation, large variation in the climate sensitivity of species groups, and uncertainties about time scales linking extinction risks to range reductions also lead to large uncertainty in model-based estimates of extinction risk.

A variety of studies since AR4 illustrate how accounting for these factors alters estimates of extinction risk. Accounting for biotic interactions such as pollination or predator-prey networks can increase modeled extinction risks, at least for certain areas and species groups (Schweiger et al., 2008; Urban et al., 2008; Hannah, 2012; Nakazawa and Doi, 2012), or can decrease extinction risk (Menéndez et al., 2008; Pateman et al., 2012). Accounting for climatic variation at fine spatial scales may increase (Randin et al., 2009; Gillingham et al., 2012; Suggitt et al., 2012; Dobrowski et al., 2013; Franklin et al., 2013) or decrease (Trivedi et al., 2008; Engler et al., 2011; Shimazaki et al., 2012) the persistence of small populations under future climate change. Several recent studies indicate that correlative species distribution models (the type of model most frequently used for evaluating species extinction risk) tend to be much more pessimistic concerning plant species range contractions and the inferred extinction risks due to climate change when compared to mechanistic models that explicitly account for the interactions between climate change and protective effects of rising CO_2 concentrations on plants (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). Models that account for population dynamics indicate that some species populations, such as those of polar bears (Hunter et al., 2010), will decline precipitously over the course of the next century due to climate change, greatly increasing extinction risk, while others may not (Keith et al., 2008). Phenotypic plasticity in one very well-studied temperate bird population has been estimated to be sufficient to keep extinction risk low even with projected warming exceeding 2–3°C (Vedder et al., 2013), but this and other studies suggest that capacity for adaptation is often substantially lower in species with long generation times (see Section 4.4.1.2). There is evidence that interactions between physiological tolerances and regional climate change will lead to large taxonomic and spatial variation in extinction risk (Deutsch et al., 2008; Sinervo et al., 2010). Even species whose populations are not projected to decline rapidly over the next century can face a substantial "extinction debt," that is, will be in unfavorable climates that over a period of many centuries are projected to lead to large reductions in population size and increase the risk of extinction (Dullinger et al., 2012). Finally, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate—with a few notable exceptions such as large land animal extinctions during the Holocene—has led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin et al., 2007; Dawson et al., 2011; Hof et al., 2011a; Willis and MacDonald, 2011; Moritz and Agudo, 2013). However, as indicated in Section 4.2.3, no past climate changes are precise analogs of future climate change in terms of speed, magnitude, and spatial scale; nor did they occur alongside the habitat modification, overexploitation, pollution, and invasive species that are characteristic of the 21st century. Therefore the paleontological record cannot easily be used to assess future extinction risk due to climate change.

4.3.3. Impacts on and Risks for Major Systems

This section covers impacts of climate change on broad categories of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those ecosystems that have high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change. Two geographical regions of particularly high risk have been identified in recent studies: (1) tropics, due to the limited capacity of species to adapt to moderate global warming and (2) high northern latitude systems, because temperature increases are projected to be large. There has been a tendency to oppose these two points of view, but there is a high risk in both types of systems, albeit for different reasons (Corlett, 2011). Tropical species, which experienced low inter- and intra-annual climate variability, have evolved within narrow thermal limits, and are already near their upper thermal limits (ectotherms: Deutsch et al., 2008; Huey et al., 2012; birds: Sekercioglu et al., 2012; trees: Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems that have evolutionary histories of climatic variability (e.g., Arctic and boreal ecosystems; Beaumont et al., 2011). However, there are physiological, evolutionary, and ecological arguments that tropical species and ecosystem sensitivities to climate change are complex and may not be particularly high compared to other systems (Gonzalez et al., 2010; Corlett, 2011; Laurance et al., 2011; Gunderson and Leal, 2012; Walters et al., 2012). High-latitude systems have the greatest projected exposure to rising temperatures (WGI AR5 Chapter 12; Diffenbaugh and Giorgi, 2012), which all else being equal would put them at higher risk. The greatest degree of recent climate warming has occurred at high northern latitudes (Burrows et al., 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez et al., 2010).

Several potential tipping points (see Section 4.2.1) with regional and global consequences have been identified (Scheffer, 2009); two are elaborated in Boxes 4-3 (Amazon dieback) and 4-4 (tundra-boreal regime shift). An assessment by the authors of this chapter of the top risks in relation to climate change and terrestrial and freshwater ecosystems is presented in Table 4-3.

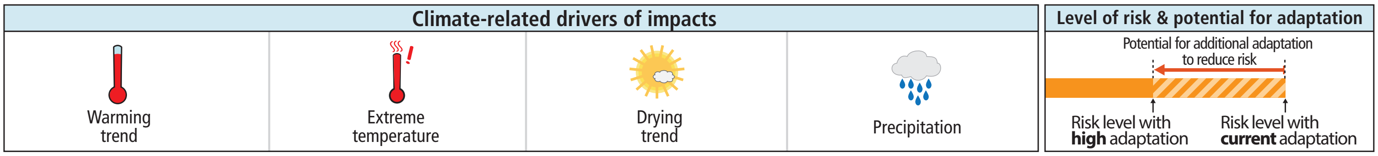
4.3.3.1. Forests and Woodlands

Forests and woodlands are principal providers of timber, pulp, bioenergy, water, food, medicines, and recreation opportunities and can play prominent roles in cultural traditions. Forests are the habitat of a large fraction of the Earth's terrestrial plant and animal species, with the highest concentrations and levels of endemism found in tropical regions (Gibson et al., 2011). Climate change and forests interact strongly; air temperature, solar radiation, rainfall, and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics, and forests help control climate through the large amounts of carbon they can remove from the atmosphere or release, through absorption or reflection of solar radiation (albedo), cooling through evapotranspiration, and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011).

Combinations of ground-based observations, atmospheric carbon budgets, and satellite measurements indicate with *high confidence* that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 860 ± 70 PgC and sequestered 4.0 ± 0.7 PgC yr^{-1} globally between 2000 and 2007 (WGI AR5 Chapter 6; Canadell et al., 2007; Pan et al., 2011; Le Quéré et al., 2012). The carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change of 2.8 ± 0.4

4

Table 4-3 | Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). For the near term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere. Key mechanisms include an increase in fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures. (*medium confidence*) [4.2.4, 4.3.2, 4.3.3]	Adaptation prospects include managing land use (including deforestation), fire, and other disturbances and non-climatic stressors.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost and spread of shrubs in tundra and increase in pests and fires in boreal forests. (*medium confidence*) [4.3.3.1.1, Box 4-4]	There are few adaptation options in the Arctic.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Amazon tipping point: Moist Amazon forests could change abruptly to less carbon-dense drought and fire-adapted ecosystems. (*low confidence*) [4.3.3.1.3, Box 4-3]	Policy and market measures to reduce deforestation and fire.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Tree mortality and forest loss: Tree mortality has been observed to have increased in many places and has been attributed in some cases to direct climate effects and indirect effects due to pests and diseases. The dead trees increase the risk of forest fires. (*medium confidence*) [4.3.3.1, Box 4-2]	Adaption options include more effective management of fire, pests, and pathogens.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Increased risk of species extinction: A large fraction of the species that have been assessed are vulnerable to extinction as a result of climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountain tops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, and especially those vulnerable to timing (phenological) changes, amplify the risk. (*high confidence*) [4.3.2.5, 4.3.3.3, 4.3.2.1, 4.4.2]	Adaptation options include reducing habitat modification, habitat fragmentation, pollution, over-exploitation, and invasive species; protected area expansion, assisted dispersal, *ex situ* conservation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Invasion by non-native species: Disruptions of species interactions and the increase in physiological stress as a result of being near the edge or outside of the historical climate niche increases the vulnerability of ecosystems to invasion by non-native (alien) species, especially in the presence of increased long-distance dispersal opportunities. In the extreme this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided. (*high confidence*) [4.2.4.6]	Climate is one driver among many. Adaptation options are limited, largely based on reducing other stresses and measures to slow the unintended arrival of aliens. Intensive direct intervention in controlling emergent invasive species is an option, but could be overwhelmed by the rapidly rising number of cases.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

PgC yr^{-1} over this same period due mostly to tropical deforestation and forest degradation associated with logging and fire, resulting in a net carbon balance for global forests of 1.1±0.8 PgC yr^{-1}.

The future of the interaction between climate and forests is unclear. The carbon taken up by intact and regrowing forests appears to have stabilized compared to the 1990s, after having increased in the 1970s and 1980s (Canadell et al., 2007; Pan et al., 2011). There is *medium confidence* that the terrestrial carbon sink is weakening. The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and stimulation of carbon sequestration by climate change, rising atmospheric CO_2 concentrations, and nitrogen deposition

(Pan et al., 2011; see also Sections 4.2.4.1, 4.2.4.2, 4.2.4.4). Most models suggest that rising temperatures, drought, and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008; Bowman et al., 2009). Fires play a dominant role in driving forest dynamics in many parts of the world; forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP2.6), but substantially for the high emissions scenario (RCP8.5; Figure 4-6). There is *low agreement* on whether climate change will cause fires to become more or less frequent in individual locations (Figure 4-6). Climate change-mediated disease and insect outbreaks could exacerbate climate-driven increases in fire susceptibility (Kurz et al., 2008). The greatest risks for large positive feedbacks from forests to climate through changes in disturbance regimes arise from widespread tree mortality and fire in tropical forests and low-latitude areas of boreal forests, as well as northward expansion of boreal forests into Arctic tundra (Lenton et al., 2008; Kriegler et al., 2009; Good et al., 2011b).

Recent evidence suggests (*low confidence*) that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru et al., 2010; Silva et al., 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks, and a wide range of other indirect impact mechanisms (Allen, C.D. et al., 2010; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions and attribution to climate change is difficult because of the multiplicity of mechanisms mediating mortality (Allen, C.D. et al., 2010).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Nepstad et al., 2009; INPE, 2013). Growing pressure for new crop (Section 4.4.4) and grazing land will continue to drive tropical deforestation (*medium confidence*), although recent policy experiments and market-based interventions in land use demonstrate the potential to reduce deforestation (Meyfroidt and Lambin, 2011; Westley et al., 2011; Nepstad et al., 2013).

4.3.3.1.1. Boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition toward more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf (Lloyd et al., 2011; Pearson et al., 2013). Projections of climate-driven changes in boreal forests over the next few centuries remain uncertain on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, nonlinear, or abrupt decline in some regions (Bernhardt et al., 2011; Mann et al., 2012; Scheffer et al., 2012; see WGI AR5 Chapter 12). Recent observed change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch et al., 2008) suggest that regions of the boreal forest could experience widespread forest dieback, although there is *low confidence* owing to conflicting results (Sitch et al., 2008; Gonzalez et al, 2010) and poor understanding of relevant mechanisms (WGI AR5 Section 12.5.5.6). If such shifts were to occur, they would put the boreal carbon sink at risk (Pan et al., 2011; Mann et al., 2012).

Whereas boreal forest productivity has been expected to increase as a result of warming (Hari and Kulmata, 2008; Bronson et al., 2009; Zhao and Running, 2010; Van Herk et al., 2011), and early analyses of satellite observations confirmed this trend in the 1980s (*medium confidence*), more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck, P.S.A. et al., 2011; de Jong et al., 2011). The best evidence to date indicates that these "browning trends" are due to warming-induced drought, specifically the greater drying power of air (vapor pressure deficit; Williams et al., 2013), inducing photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008; Van Herk et al., 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber et al., 2000; Hogg et al., 2008; Beck, P.S.A. et al., 2011; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng et al., 2011; Ma et al., 2012). Conversely, productivity has increased at the boreal-tundra ecotone, where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (Rupp et al., 2001; McGuire et al., 2007; Goldblum and Rigg, 2010; Beck, P.S.A. et al., 2011). The complexity of boreal forest response also involves tree age and size, with younger trees and stands perhaps being more able to benefit from warming where other factors are not limiting (Girardin et al., 2011, 2012).

Where they occur, warming and drying, coupled with productivity declines, insect disturbance, and associated tree mortality, also favor greater fire disturbance (*high confidence*). The boreal biome fire regime has intensified regionally in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke et al., 2010; Turetsky et al., 2011; Mann et al., 2012; Girardin et al., 2013a). The latter is particularly important because more severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favor recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest (Johnstone et al., 2010; Bernhardt et al., 2011). Fire-mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes in net ecosystem carbon balance (Bond-Lamberty et al., 2007; Goetz et al., 2007; Welp et al., 2007; Euskirchen et al., 2009) as well as albedo and energy balance (Randerson et al., 2006; Jin et al., 2012; O'Halloran et al., 2012). The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained owing to sparse *in situ* observations.

The vulnerability of the boreal biome to this cascading series of interacting processes (Wolken et al., 2011), and their ultimate influence on climate

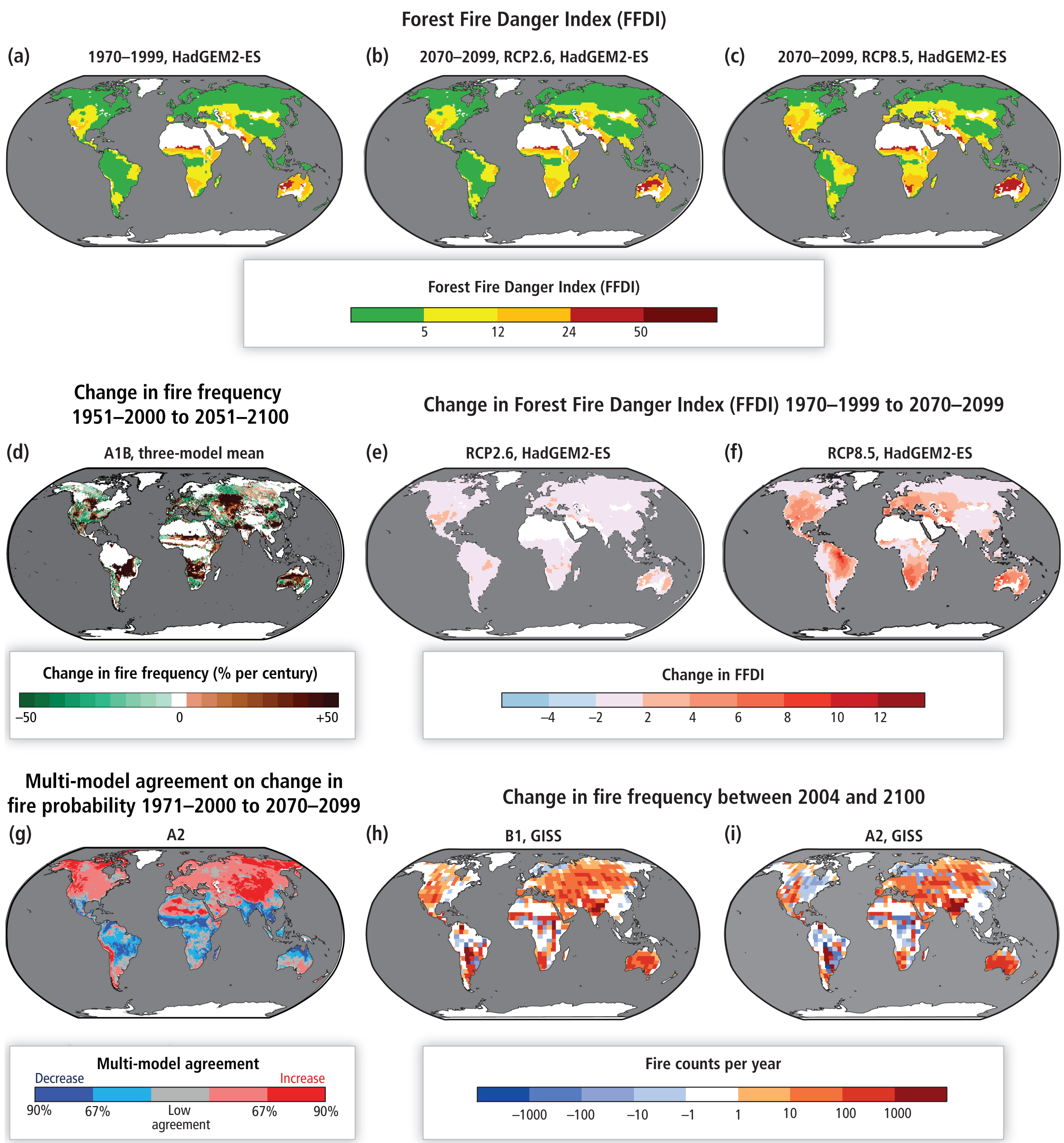


Figure 4-6 | Projected changes in meteorological fire danger, fire probability, and fire frequency with different methods and climate models. (a) 30-year annual mean McArthur Forest Fire Danger Index (FFDI) and change simulated with the Hadley Centre Global Environmental Model version 2 Earth System configuration (HadGEM2-ES) for 1970–1999, with areas of no vegetation excluded (Betts et al., 2013). (b) As (a) for 2070–2099, Representative Concentration Pathway 2.6 (RCP2.6). (c) as (a) for 2070–2099, RCP8.5. (d) Change in fire frequency by 2051–2100 relative to 1951–2000, SRES A1B, simulated with the MC1 vegetation model driven by three GCMs (Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3.0, Met Office Hadley Centre Coupled Model version 3 (HadCM3), Model for Interdisciplinary Research On Climate (MIROC) 3.2medres; mean over three simulations; Gonzalez et al., 2010). (e) Difference between (b) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP2.6. (f) Difference between (c) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP8.5. (g) Agreement on changes in fire probability by 2070–2099 relative to 1971–2000 (Moritz et al., 2012) simulated with a statistical model using climate projections from 16 Coupled Model Intercomparison Project Phase 3 (CMIP3) GCMs, Special Report on Emission Scenarios (SRES) A2. (h) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the Goddard Institute of Space Studies General Circulation Model (GISS GCM) (AR4 version) and Integrated Model to Assess the Global Environment Integrated Assessment Model (IMAGE IAM) (Pechony and Shindell, 2010). (i) As (h) for SRES A2. Changes in FFDI (a), (b), (c), (e), (f) and fire probability (g) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (d), (h), (i) depend on both meteorological quantities and vegetation.

feedbacks, differs between North America and northern Eurasia (*high confidence*). The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia—a region more than twice the size of the North American boreal biome, most of it underlain by permafrost. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa et al., 2010; Alexander et al., 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in parts of North America (Soja et al., 2007; Ali et al., 2012; Mann et al., 2012; Marlon et al., 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region. In summary, an increase in tree mortality is observed in many boreal forests, with the clearest indicators of this in North America. However, tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection and attribution of a clear temporal trend in tree mortality at the global scale (Figure 4-4).

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (*high confidence*; Schuur et al., 2008, 2009, 2013; Tarnocai et al., 2009; Romanovsky et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang et al., 2011). The degree of thermokarsting (melting of ice-rich soil) associated with different substrates and associated topographic relief is variable because boreal vegetation in later successional stages (evergreen conifers in North America) insulates permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and because of other factors such as the reduction of insulation provided by vegetation cover and soil organic layers due to increased fire (Jorgenson et al., 2010; Grosse et al., 2011). This variability and vulnerability is poorly represented in ESMs (McGuire et al., 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example, by removing forest cover to expose the land surface to winter temperatures (Zimov et al., 2009), are impractical, not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Temperate forests

The largest areas of temperate forest are found in eastern North America, Europe, and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition, and forest management—specifically regrowth following formerly more intensive harvesting regimes (Ciais et al., 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence* and *high agreement*), absorbing 0.70 $\pm$ 0.08 PgC yr^{-1} from 1990 to 1999 and 0.80 $\pm$ 0.09 from 2000 to 2007 (Pan et al., 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including a reversal of tree growth enhancement in some regions (North America: Silva et al., 2010; Silva and Anand, 2013; Europe: Charru et al., 2010; Bontemps et al., 2011; Kint et al., 2012); increasing tree mortality (Allen, C.D. et al., 2010; Box 4-2); and changes in fire regimes, insect outbreaks, and pathogen attacks (Adams et al., 2012; Edburg et al., 2012). In northeastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica* L.) have been attributed to decreasing water availability (Charru et al., 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heat waves (Charru et al., 2010; Silva et al., 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Ciais et al., 2005; Witte et al., 2011; Kasson and Livingston, 2012). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte et al., 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen, C.D. et al., 2010). There is *low confidence* (*limited evidence*, *medium agreement*) that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of Dynamic Global Vegetation Models (DGVMs) showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially through gains in forest cover; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch et al., 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (Sitch et al., 2008; Peng et al., 2009; Ni, 2011). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change

Box 4-2 | Tree Mortality and Climate Change

Extensive tree mortality and widespread forest dieback (high mortality rates at a regional scale) linked to drought and temperature stress have been documented recently on all vegetated continents (Allen, C.D. et al., 2010; Figure 4-7). However, appropriate field data sets are currently lacking for many regions (Anderegg et al., 2013a), leading to *low confidence* in our ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem et al., 2009; Peng et al., 2011). Increased levels of tree mortality following drought episodes have also been detected in multiple tropical forests (Kraft et al., 2010; Phillips et al., 2010) and Europe (Carnicer et al., 2011). Episodes of widespread dieback (high mortality rates at a regional scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa et al., 2008; Carnicer et al., 2011; Anderegg et al., 2013a). Some widespread dieback events have occurred concomitant with infestation outbreaks (Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011), where insect populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz et al., 2010). Although strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is low confidence that this attribution can be made at the global scale.

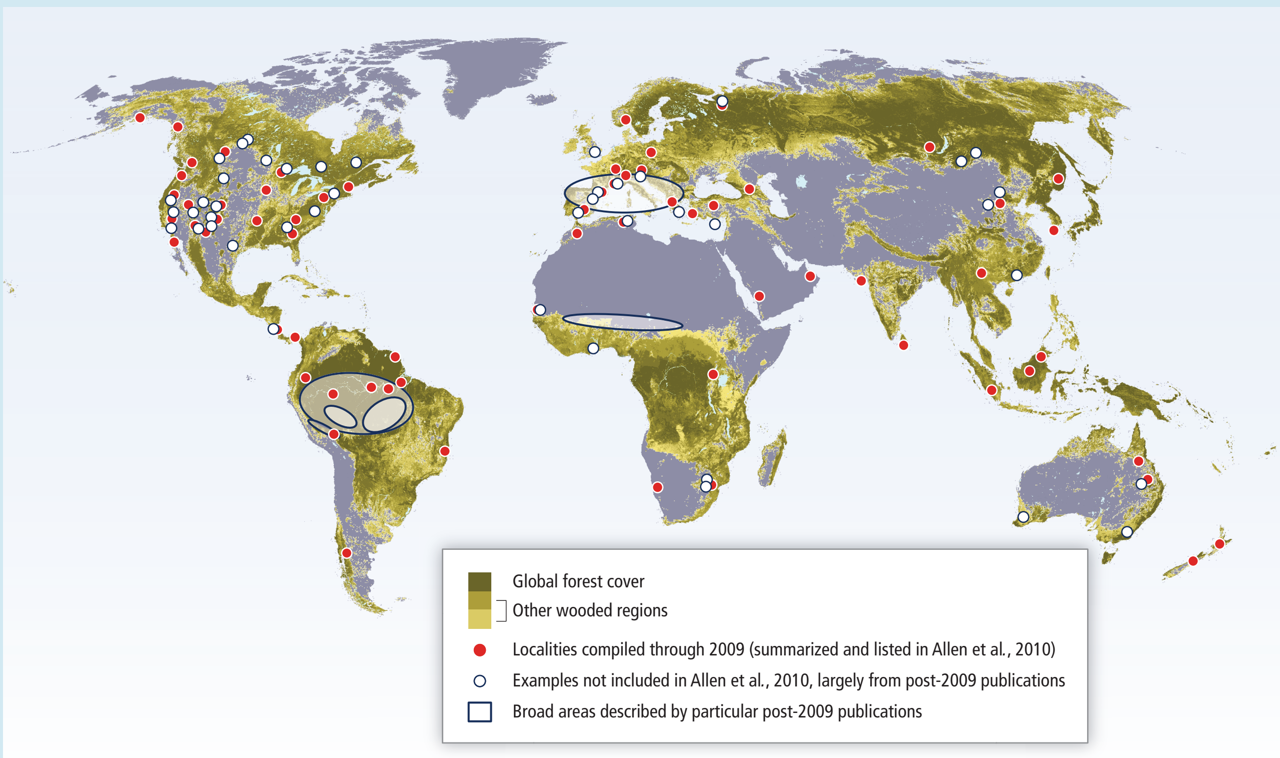


Figure 4-7 | Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen, C.D. et al. (2010). Localities and measurement networks not included in Allen, C.D. et al. (2010), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa: Mehl et al., 2010; van der Linde et al., 2011; Fauset et al., 2012; Gonzalez et al., 2012; Kherchouche et al., 2012; Asia: Dulamsuren et al., 2009; Kharuk et al., 2013; Liu et al., 2013; Zhou et al., 2013; Australasia: Brouwers et al., 2012; Fensham et al., 2012; Keith et al., 2012; Matusick et al., 2012; Brouwers et al., 2013; Matusick et al., 2013; Europe: Innes, 1992; Peterken and Mountford, 1996; Linares et al., 2009; Galiano et al., 2010; Vennetier and Ripert, 2010; Aakala et al., 2011; Carnicer et al., 2011; Linares et al., 2011; Sarris et al., 2011; Marini et al., 2012; Cailleret et al., 2013; Vilà-Cabrera et al., 2013; North America: Fahey, 1998; Minnich, 2007; Klos et al., 2009; Ganey and Vojta, 2011; Michaelian et al., 2011; Peng et al., 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser et al., 2012; Millar et al., 2012; Garrity et al., 2013; Kukowski et al., 2013; Williams et al., 2013; Worrall et al., 2013; South America: Enquist and Enquist, 2011; Lewis et al., 2011; Saatchi et al., 2013.

Continued next page →

Box 4-2 (continued)

Forest dieback has influenced the species composition, structure and age demographics, and successional trajectories in affected forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane et al., 2011; Anderegg et al., 2012). Widespread tree mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears et al., 2005; Kurz et al., 2008; Anderson et al., 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell et al., 2011). Most current vegetation models have little-to-no mechanistic representation of tree mortality (Fisher et al., 2010; McDowell et al., 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat et al., 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semiarid forests. Furthermore, time scales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several forests indicates that full recovery times may be longer than drought return intervals, leading to "compounding" effects of multiple droughts (Mueller et al., 2005; Anderegg et al., 2013b; Saatchi et al., 2013). Projected increases in temperature are also expected to facilitate expansion of insect pest outbreaks poleward and in altitude, which may also cause or contribute to tree mortality (Bentz et al., 2010).

are characterized by tipping points (Bonan, 2008). There is *low confidence* (*medium evidence*, *low agreement*) on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and to higher altitude in response to climate change (Dale et al., 2010; Ogawa-Onishi et al., 2010; Hickler et al., 2012). Associated long-term projected range shifts generally vary from several kilometers to several tens of kilometers per decade, most probably faster than natural migration (e.g., Chmura et al., 2011; see also Section 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see Section 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g., Dale et al., 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Morin and Thuiller, 2009; Kearney et al., 2010; Kramer et al., 2010; Cheaib et al., 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the 21st century in China (Ni, 2011). New approaches to modeling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin et al., 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman et al., 2008; Allen, J.R.M. et al., 2010; Garreta et al., 2010). Model projections are qualitatively coherent with observations that temperate forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir et al., 2008). There is *medium confidence* (*medium evidence*, *medium agreement*) that temperate tree species are migrating poleward and to higher altitudes.

4.3.3.1.3. Tropical forests

Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes (Malhi et al., 2008; Davidson et al., 2012).

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see Section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008), although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass (Körner and Basler, 2010). DGVMs and the current generation of ESMs, including those used within CMIP5 (e.g., Jones et al., 2011; Powell et al., 2013), generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar et al., 1980; Ball et al., 1987; Stewart, 1988; Collatz et al., 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox et al., 1998) that predates larger ecosystem-scale studies, although some models have been calibrated on the basis of more recent data (Jones et al., 2011).

A second important source of uncertainty is the rate of future CO_2 rise and climate change (Betts et al., 2012). Modeled simulations of future climate in tropical forest regions indicate with *high confidence* (*robust evidence*, *high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between

4

climate models (WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections), although there is *medium confidence* (*medium evidence*, *medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation and more severe drought (Malhi et al., 2009a; Shiogama et al., 2011). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze et al., 2006; Sitch et al., 2008; Zelazowski et al., 2011). Recent model studies (Malhi et al., 2009a; Cox et al., 2013; Huntingford et al., 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is less likely to undergo major retractions or expansions by 2100 than was suggested in AR4. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with sea surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011). There is *low confidence*, however, that these droughts or the observed sea surface temperatures can be attributed to climate change.

Networks of long-term forest plots reveal that lianas and fast-growing tree species are increasing, as is forest biomass (Phillips et al., 2002, 2005; Lewis et al., 2009a,b, 2011). Faster tree growth is consistent with increasing WUE associated with the rising concentration of CO_2, but also with changes in solar radiation and the ratio of diffuse to direct radiation (Lewis et al., 2009a; Mercado et al., 2009; Brando et al., 2010; see also Section 4.2.4.5). There is *low confidence* (*limited evidence*, *medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood et al., 2012), but is not yet observed as changes in forest biomass (except Clark et al., 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in these ecosystems, and to the importance of extreme drought events (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad et al., 2007; Fisher et al., 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando et al., 2012). These experimental results were corroborated by observations of increased tree mortality during the severe 2005 drought in the Amazon (Phillips et al., 2009) and extensive forest fire (Alencar et al., 2006, 2011; Aragão et al., 2008; Box 4-3). There is *high confidence* (*medium evidence*, *high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods.

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy, and allowing greater heating of the forest interior (Uhl and Kauffman, 1990; Curran et al., 2004; Ray et al., 2005; Box 4-3). Land use also often increases the ignition sources in tropical landscapes (Silvestrini et al., 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence*, *high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use. There is *medium confidence* (*medium evidence*, *high agreement*) that tree mortality in the Amazon region is increasing through severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Figure 4-4).

Dry tropical forests are defined by strong seasonality in rainfall distribution (Mooney et al., 1995) and have been reduced to an estimated 1 million km^2 globally through human activities (Miles et al., 2006). Half of the world's remaining dry tropical forests are located in South America. Using five climate model simulations for the 2040–2069 period under the IS92a "business-as-usual scenario," Miles et al. (2006) found that approximately one-third of the remaining area of tropical dry forests in the Americas will be exposed to higher temperatures and lower rainfall through climate change. Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk of replacement or degradation (Miles et al., 2006). In a regional study a dynamic vegetation model (Integrated Biosphere Simulator (IBIS)) under A2 and B2 scenarios projected by a global climate model (Hadley Centre Regional Model 3 (HadRM3)) found that most of the dry forests of India would be outside of their climate envelopes later in this century (Chaturvedi et al., 2011). There is *low confidence* in our understanding of climate change effects on dry forests globally.

4.3.3.2. Dryland Ecosystems: Savannas, Shrublands, Grasslands, and Deserts

The following sections treat a wide range of terrestrial ecosystems covering a large part of the land surface, whose common features are that they typically exhibit strong water stress for several months each year and grass-like plants and herbs are a major part of their vegetation cover. Thus the principal land use often involves grazing by domestic livestock or wild herbivores.

4.3.3.2.1. Savannas

Savannas are mixtures of coexisting trees and grasses, covering about a quarter of the global land surface, including tropical and temperate forms. Savannas are characterized by annual to decadal fires (Archibald et al., 2009) of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major and climate-sensitive global source of fire-related emissions from land to atmosphere (Schultz et al., 2008; van der Werf et al., 2010). The geographical distribution of savannas is determined by temperature, the seasonal availability of water, fire, and soil conditions (Ellery et al., 1991; Walker and Langridge, 1997; Staver et al., 2011) and is therefore inferred to be susceptible to climate change. In parts of Central Africa, forests have been observed to be

Box 4-3 | A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-driven, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon "forest dieback") has improved. Modeling studies indicate that the likelihood of a climate-driven forest dieback by 2100 is lower than previously thought (Malhi et al., 2009b; Cox et al., 2013; Good et al., 2013; Huntingford et al., 2013), although lower rainfall and more severe drought is expected in the eastern Amazon (Malhi et al., 2009a). There is now *medium confidence* (*medium evidence*, *medium agreement*) that climate change alone (i.e., through changes in the climate envelope, without invoking fire and land use) will not drive large-scale forest loss by 2100 although shifts to drier forest types are predicted in the eastern Amazon (Mahli et al., 2009a). Meteorological fire danger is projected to increase in some models (Golding and Betts, 2008; Betts et al., 2013; Figure 4-6). Field studies and regional observations have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land use activities that could drive a fire-mediated, self-reinforcing dieback during the next few decades (Figure 4-8). There is now *medium confidence* (*medium evidence*, *high agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured fire-adapted woody vegetation.

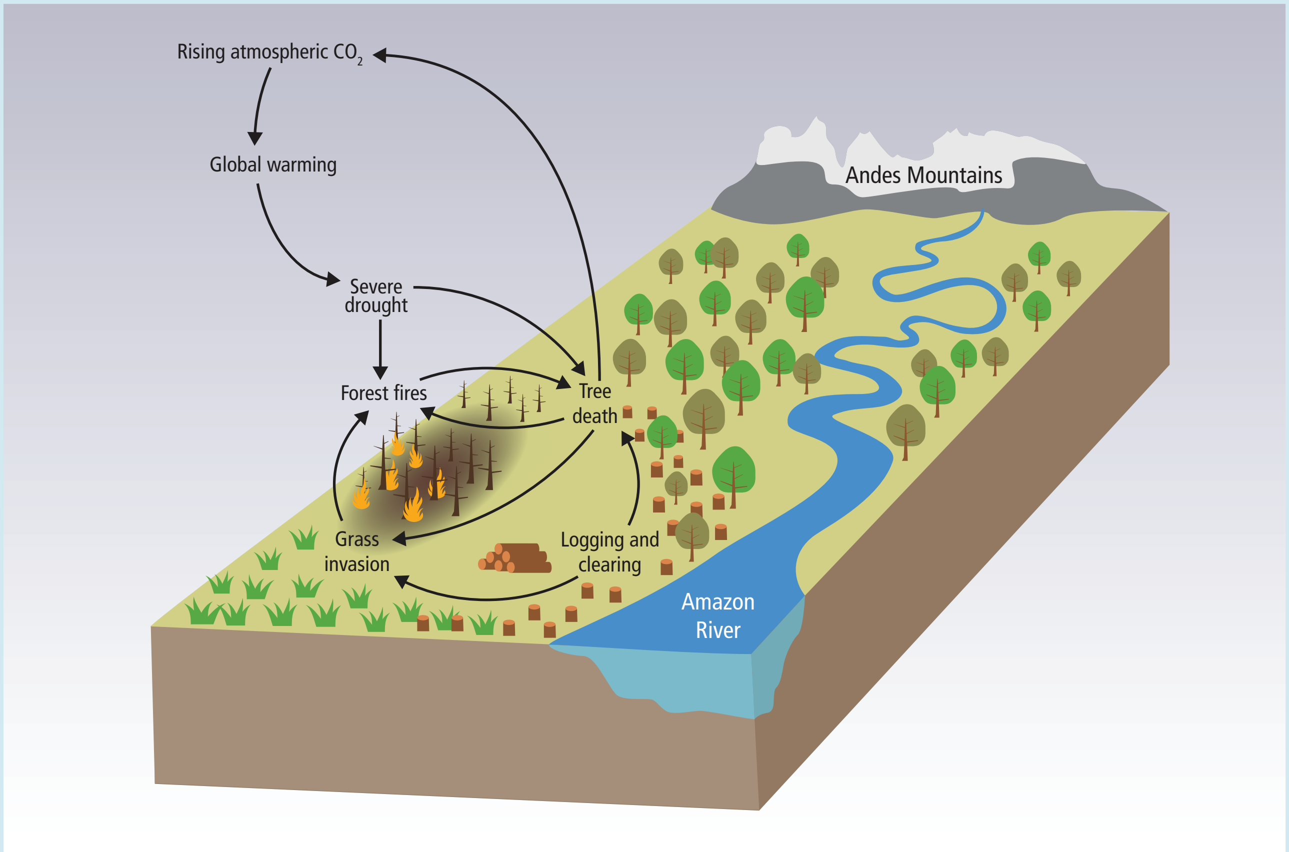


Figure 4-8 | The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence*; *medium evidence*, *medium agreement*).

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4

Box 4-3 (continued)

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray et al., 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray et al., 2005; Barlow and Peres, 2008), previous forest fire (Balch et al., 2008; Brando et al., 2012), severe drought (Alencar et al., 2006), or drought-induced tree mortality (Nepstad et al., 2007; da Costa et al., 2010). The impact of fire on tree mortality is also weather dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando et al., 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence*, *high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Fire ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini et al., 2011) (*high confidence*: *robust evidence*, *high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa et al., 2007; Butt et al., 2011; Knox et al., 2011) (*low confidence*: *medium evidence*, *low agreement*) or through smoke, which can inhibit rainfall under some circumstances (Andreae et al., 2004) (*medium confidence*: *medium evidence*, *medium agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Mahli et al. 2009b; Shiogama et al., 2011).

If recent patterns of deforestation (through 2005), logging, severe drought, and forest fire continue into the future, more than half of the region's forests will be cleared, logged, burned, or exposed to drought by 2030, even without invoking positive feedbacks with regional climate, releasing 20 ± 10 PgC to the atmosphere (Nepstad et al., 2008) (*low confidence*: *low evidence*, *medium agreement*) (Figure 4-8). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo et al., 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished on a large scale (Soares-Filho et al., 2012), if deforestation declines, or if cleared lands are reforested (Nepstad et al., 2008). The 77% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2013) demonstrates that policy-led avoidance of a fire-mediated tipping point is plausible.

moving into adjacent savannas and grasslands (Mitchard et al., 2009), possibly due to depopulation and changes in the fire regime. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Bowman et al., 2011; Tng et al., 2012). It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to former forested areas becoming savannas in parts of the Amazon basin (Malhi et al., 2009b; Box 4-3). In many places around the world the savanna boundary is moving into former grasslands on elevation gradients; in other words, into areas inferred to be formerly too cool for trees (Breshears, 2006).

The proportion of trees and grasses in savannas is considered unstable under some conditions (De Michele et al., 2011; Staver et al., 2011). The differential effects of climate change, rising CO_2, fire, and herbivory on trees and grasses have the potential to alter the tree cover in savannas, possibly abruptly. There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*robust evidence*, *high agreement*; Moleele et al., 2002; Angassa and Oba, 2008; Cabral et al., 2009; Wigley et al., 2009; Witt et al., 2009; Lunt et al., 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area in form of tree biomass and soil organic matter (Hughes et al., 2006; Liao et al., 2006; Knapp et al., 2007; Throop and Archer, 2008; Boutton et al., 2009), changes in hydrology (Muñoz-Robles et al., 2011), and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert et al., 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf et al., 2012), climate variability and change (Eamus and Palmer, 2007; Fensham et al., 2009), or several of these factors acting in combination (Ward, 2005). As yet, there are no studies that definitively attribute the relative importance of the climate- and non-climate-related causes of woody plant biomass increase in savannas (and the invasion of trees into former grasslands), but there is *medium agreement* and *robust evidence* that climate change and rising CO_2 are contributing factors in many cases. The increased growth rate of C_3 photosynthetic system trees relative to C_4

grasses under rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope et al., 2010).

A model of grasslands, savannas, and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position, or soil depth (Wiegand et al., 2005; Wu and Archer, 2005) imply that land management, water balance, and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran et al., 2005), suggesting that future increases in rainfall projected for most but not all savanna areas (WGI AR5 Annex I: Atlas of Global and Regional Climate Projections) could lead to increased tree biomass.

4.3.3.2.2. Grasslands and shrublands

Rangelands (partly overlapping with savannas) cover approximately 30% of the Earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon (Booker et al., 2013). Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition, and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (*high confidence*) (e.g., Sala et al., 1988; Snyman and Fouché, 1993; Fay et al., 2003; Peñuelas et al., 2004, 2007; Prieto et al., 2009; Peters et al., 2010; Martí-Roura et al., 2011; Booker et al., 2013; Wu and Chen, 2013). Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon, plant, and soil nutrient contents (e.g., Fay et al., 2003; Peñuelas et al., 2004, 2007; Beier et al., 2008; Sardans et al., 2008a,b; Sowerby et al., 2008; Liu et al., 2009; Miranda et al., 2009; Albert et al., 2011, 2012; Selsted et al., 2012; Walter et al., 2012).

Precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompany warming (Engler et al., 2011). Responses of shrublands to drought may be driven partly by changes in the soil microbial community (Jensen et al., 2003) or changes in soil fauna (Maraldo et al., 2008). An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby et al., 2008, 2010). Simulated increased spring temperature and decreased summer precipitation had a general negative effect on plant survival and plant growth, irrespective of the macroclimatic niche characteristics of the species. Against expectation, species with ranges extending into drier regions did not generally perform better under drier conditions (Bütof et al., 2012).

Changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world, with increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation) and changes in hydrology and the erosion of soil by wind (Ravi et al., 2010). In mixed shrub grasslands, the influence of drought periods could produce transient pulses of carbon that are much larger than the pulses produced by fire (Martí-Roura et al., 2011). Most studies of changes in arid systems between grasslands and shrublands have focused on plant-soil feedbacks that favor shrub growth. Summers drier than three-quarters of current rainfall decreased grass seedling recruitment to negligible values (Peters et al., 2010). Management cannot reliably increase carbon uptake in arid and semiarid rangelands, which is most often controlled by abiotic factors not easily changed by management of grazing or vegetation (Booker et al., 2013).

Other factors being equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production (*limited evidence*, *low agreement*). A shift to more woody vegetation states expected to occur (locally but not globally) in tropical grasslands of the African continent (Higgins and Scheiter, 2012). The response to warming and drought depends on site, year, and plant species, as shown by manipulation experiments (Peñuelas et al., 2004, 2007; Gao and Giorgi, 2008; Grime et al., 2008; Shinoda et al., 2010; Wu and Chen, 2013). In most temperate and Arctic regions, the capacity to support richer (i.e., more diverse) communities is projected to increase with rising temperature, while decreases in water availability suggest a decline in capacity to support species-rich communities in most tropical and subtropical regions (Sommer et al., 2010). Warming may cause an asymmetrical response of soil carbon and nitrogen cycles, causing nitrogen limitation that reduces acclimation in plant production (Beier et al., 2008).

Some grasslands are exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point, and decreases it thereafter (see Section 4.2.4.2; Bobbink et al., 2010; Cleland and Harpole, 2010; Gaudnik et al., 2011). In a study of 162 plots over 25 years, nitrogen deposition drove grassland composition at the local scale, in interaction with climate, whereas climate changes were the predominant driver at the regional scale (Gaudnik et al., 2011). Nitrogen mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions (Emmett et al., 2004). Decreased tissue concentrations of phosphorus were also associated with warming and drought (Peñuelas et al., 2004, 2012; Beier et al., 2008). Strong interactions between warming and disturbances have been observed, leading to increased nitrogen leaching from shrubland ecosystems (Beier et al., 2004).

Most grasslands and shrublands are characterized by relatively frequent but low-intensity fires, which affect their plant species composition and demographics (e.g., Gibson and Hulbert, 1987; Gill et al., 1999; Uys et al., 2004; de Torres Curth et al., 2012). Species composition changes may be as important in determining ecosystem impacts as the direct effects of climate on plant (Suttle et al., 2007). Fire frequency, duration, and intensity are influenced primarily by climate and secondarily by management (Pitman et al., 2007; Lenihan et al., 2008; Archibald et al., 2009; Giannakopoulos et al., 2009; Armenteras-Pascual et al., 2011), and are therefore sensitive to climate change; the duration of the fire season is also projected to broaden (Clarke et al., 2013). Changes in fire frequency may interact with changes in rainfall seasonality: for instance, if fires are followed by rainy spring periods in northwestern Patagonia, as occurs with more frequent El Niño-Southern Oscillation (ENSO) phenomena, there are more recruitment windows for shrubs (Ghermandi et al., 2010). Relatively little is known regarding the combined effect of climate change and increased grazing by large mammals, or on the consequences for pastoral livelihoods that depend on rangelands (Thornton et al., 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35% of the global land surface. Species composition in desert areas is expected to shift in response to climate warming (Ooi et al., 2009; Kimball et al., 2010). Deserts are sparsely populated, but the people who do live there are among the poorest in the world (Millennium Ecosystem Assessment, 2005a). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley Circulation, which determines the location of the broad band of hot deserts approximately 15°N to 30°N and 15°S to 30°S of the equator (Mitas and Clement, 2005; Seidel et al., 2008; Johanson and Fu, 2009; Lu et al., 2009; Zhou et al., 2011). There may be a feedback to the global climate from an increase in desert extent, which differs in sign between deserts closer to the equator than 20° and those closer to the pole: in model simulations, extension of the near-equator "hot deserts" causes warming, while extension of the near-boreal "cold deserts" causes cooling, in both cases largely through albedo-mediated effects (Alkama et al., 2012). Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola et al., 2009; Stahlschmidt et al., 2011). Most deserts are already extremely hot, and therefore further warming likely to be physiologically injurious rather than beneficial. The ecological dynamics in deserts are rainfall event-driven (Holmgren et al., 2006), often involving the concatenation of a number of quasi-independent events. Some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change (Lapola et al., 2009; Stahlschmidt et al., 2011).

4.3.3.2.4. Mediterranean-type ecosystems

Mediterranean-type ecosystems occur on most continents, and are characterized by cool, wet winters and hot, dry summers. They were identified as being among the most likely to be impacted by climate change in AR4 and received extensive coverage (Fischlin et al., 2007). Since then, further evidence has accumulated of climate risks to these systems from rising temperature (Giorgi and Lionello, 2008), rainfall change (declining in most but not all cases), increased drought (Sections 23.2.3, 25.2), and increased fire frequency (Section 23.4.4). There have been observed shifts in phenology (Gordo and Sanz, 2010), range contraction of Mediterranean species (Pauli et al., 2012), declines in the health and growth rate of dominant tree species (Allen, C.D. et al., 2010; Sarris et al., 2011; Brouwers et al., 2012; see also Section 23.4.4), and increased risk of erosion and desertification, especially in very dry areas (Lindner et al., 2010; Shakesby, 2011). Model projections show further species range contractions in the 21st century under all climate change scenarios. This will result in losses of biodiversity (*medium confidence*) (Maiorano et al., 2011; Kuhlmann et al., 2012; see also Sections 23.6.4, 25.1).

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon et al., 2006; Vörösmarty et al., 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001; Bunn and Arthington, 2002; Nilsson et al., 2005; Reidy Liermann et al., 2012). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally disconnected from their rivers (Tockner et al., 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwaters have some of the highest rates of extinction of any ecosystem for those species groups assessed for the IUCN Red List (estimated as much as 4% per decade for some groups, such as crayfish, mussels, fishes, and amphibians in North America) (Dudgeon et al., 2006), with estimates that roughly 10,000 to 20,000 freshwater species are extinct or imperilled as a consequence of human activity (Strayer and Dudgeon, 2010). This is a particular concern given that freshwater habitats support 6% of all described species (Dudgeon et al., 2006), including approximately 40% of the world's fish diversity and a third of the vertebrate diversity (Balian et al., 2008).

It is *very likely* that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and expansion of irrigated agriculture (Vörösmarty et al., 2000; Malmqvist et al., 2008; Dise, 2009). However, climate change will have significant additional impacts (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes, and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including Arctic and sub-Arctic bog communities on permafrost, and alpine and Arctic streams and lakes (see Section 4.3.3.4; Klanderud and Totland, 2005; Smith et al., 2005; Smol and Douglas, 2007b). It is noteworthy that these high-latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty et al., 2010). It is likely that the shrinkage and disappearance of glaciers will lead to the reduction of local and regional freshwater biodiversity, with 11 to 38% of the regional macroinvertebrate species pool expected to be lost following complete disappearance of glaciers (Jacobsen et al., 2012; Box CC-RF). Shrinkage of glaciers and the loss of small glaciers will most likely reduce beta diversity at the species and the genetic level, as predicted for the Pyrenees (Finn et al., 2013). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also likely to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

There is widespread evidence of rising stream and river temperatures over the past few decades (Langan et al., 2001; Morrison et al., 2002; Webb and Nobilis, 2007; Chessman, 2009; Ormerod, 2009; Kaushal et al., 2010; van Vliet et al., 2011; Markovic et al., 2013; but see Arismendi et al., 2012). Rising water temperature has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold stenothermic species (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; Ormerod, 2009). Rising temperature is also implicated in species range shifts (e.g., Comte and Grenouillet, 2013), implying changes in the composition of river fish communities (Daufresne and Boet, 2007; Buisson et al., 2008; Comte et al., 2013), especially in headwater streams where species are more sensitive to warming (e.g., Buisson and Grenouillet, 2009).

Rising temperatures in the well-mixed surface waters in many temperate lakes, resulting in reduced periods of ice formation (Livingstone and Adrian, 2009; Weyhenmeyer et al., 2011) and earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler, 2004), are projected to favor a shift in dominance to smaller phytoplankton (Parker et al., 2008; Winder et al., 2009; Yvon-Durocher et al., 2011) and cyanobacteria (Wiedner et al., 2007; Jöhnk et al., 2008; Paerl et al., 2011), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009); with impacts to water quality, food webs, and productivity (O'Reilly et al., 2003; Verburg et al., 2003; Gyllström et al., 2005; Parker et al., 2008; Shimoda et al., 2011). Prolonged stratification and associated anaerobic conditions near the sediment-water interface can increase the internal loading of phosphorus, particularly in eutrophic lakes (Søndergaard et al., 2003; Wilhelm and Adrian, 2008; Wagner and Adrian, 2009).

In many freshwater ecosystems, the input of dissolved organic carbon through runoff from the catchment has increased, inducing changes in water color (Hongve et al., 2004; Evans et al., 2005; Erlandsson et al., 2008). Soil recovery from acidification and changed hydrological conditions (partly linked to increased precipitation) appear to be the main factors driving this development (Evans et al., 2005; Monteith et al., 2007). The resulting increased light attenuation can lead to lower algal concentrations and loss of submersed vegetation (Ask et al., 2009; Karlsson et al., 2009).

Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta et al., 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer et al., 2007), noting that warming may increase species richness in smaller temperate water bodies, especially those at high altitude (Rosset et al., 2010). Although less studied, it has been proposed that tropical ectothermic ("cold blooded") organisms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high-latitude environments, despite lower rates of warming (Deutsch et al., 2008; Hamilton, 2010; Laurance et al., 2011).

There is growing evidence that climate-induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*high confidence* in detection, *medium confidence* in attribution; see Box CC-RF; Xenopoulos et al., 2005; Aldous et al., 2011). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g., Australia, California, and South Africa) are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães et al., 2007; Hermoso and Clavero, 2011) and floods (Meyers et al., 2010). Shifts in hydrologic regimes in snowmelt systems, including earlier runoff and declining base flows in summer (Stewart et al., 2005; Stewart, 2009), are projected to alter freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased interannual variability will most likely increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm et al., 2003), reduction in floodplain egg and seed banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Johnson et al., 2005; Bond et al., 2008; Sheldon et al., 2010), altered freshwater food webs (Ledger et al., 2013), and drying out of wetlands (Davis, J.L. et al., 2010).

Climate-induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a Sphagnum dominated to vascular plant dominated vegetation type and a general decline of carbon sequestration in the long term (Limpens et al., 2008). Mire ecosystems (i.e., bogs, transition bogs, and fens) in central Europe face severe climate-induced risk, with increased summer temperatures being particularly important (Essl et al., 2012). Decreased dry season precipitation and longer dry seasons in major tropical peatland areas in Southeast Asia are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li et al., 2007; Rieley et al., 2008; Frolking et al., 2011).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one-third of the world's soil carbon stock (400 to 600 Pg) (Limpens et al., 2008; Frolking et al., 2011; Page et al., 2011). About 14 to 20% of the world's peatlands are currently used for agriculture (Oleszczuk et al., 2008) and many, particularly peat swamp forests in Southeast Asia, are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens et al., 2008; Hooijer et al., 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 59.4 ± 10.2 Mg CO_2 ha^{-1} yr^{-1} over 25 years (Murdiyarso et al., 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page et al., 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking et al., 2011), though interannual variability is large. Fluvial export can also be a significant contributor to carbon losses that has been largely overlooked to date, with recent estimates of DOC export from degraded tropical peatlands 50% higher than in intact systems (Moore et al., 2013). Conserving peatland areas not yet developed for biofuels or other crops, or rewetting and restoring degraded peatlands to preserve their carbon store, are potential mitigation strategies.

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on water birds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine et al., 2010; Traill et al., 2010), but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas, and water (Syvitski et al., 2009; see Section 5.4.2.7). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke et al., 2007).

4.3.3.4. Tundra, Alpine, and Permafrost Systems

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman et al., 2009; see WGI AR5 Chapter 2). Changes consistent with warming are evident in the freshwater and terrestrial ecosystems and permafrost of the region (Hinzman et al., 2005; Axford et al., 2009; Jia, G.J. et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Romanovsky et al., 2010; Walker et al., 2012). Most of the Arctic has experienced recent change in vegetation photosynthetic capacity, particularly adjacent to rapidly retreating sea ice (Bhatt et al., 2010). Changes in terrestrial environments in Antarctica have also been reported. Vieira et al. (2010) show that in in the Maritime Antarctic permafrost temperatures are close to thaw. Permafrost warming has been observed in continental Antarctica (Guglielmin and Cannone, 2012) and for the Palmer archipelago (Bockheim et al., 2013).

Continued warming is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially (*high confidence*). Continued expansion in woody vegetation cover in tundra regions over the 21st century is projected by the CMIP5 ESMs (Bosio et al., 2012; see WGI AR5 Chapter 6), by dynamic global vegetation models driven by other climate model projections, and by observationally based statistical models (Pearson et al., 2013). Changes may be complex (see Box 4-4) and in some cases involve nonlinear and threshold responses to warming and other climatic change (Hinzman et al., 2005; Mueller, D.R. et al., 2009; Bonfils et al., 2012). Arctic vegetation change is expected to continue long after any stabilization of global mean temperature (see WGI AR5 Chapter 6; Falloon et al., 2012). In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized GHG concentrations (Falloon et al., 2012).

In the Arctic tundra biome (in contrast to the boreal forests discussed in Section 4.3.3.1.1), vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Stow et al., 2007; Jia, G.J. et al., 2009; de Jong et al., 2011; Myers-Smith et al., 2011; Elmendorf et al., 2012). This phenomenon is amplified by retreat of coastal sea ice (Bhatt et al., 2010) and has been widely discussed in the context of increased shrub growth and expansion over the last half century (Forbes et al., 2010; Myers-Smith et al., 2011). Deciduous shrubs and graminoids respond to warming with increased growth (Walker, 2006; Epstein et al., 2008; Euskirchen et al., 2009; Lantz et al., 2010). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated tundra areas (Jia, G.J. et al., 2009; Beck and Goetz, 2011); thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. The very large spatial scale over which these changes are occurring, the strong warming signal over much of the Arctic for the last 5 decades (Burrows et al., 2011), and the absence of strong confounding factors means that detection of these changes in Arctic systems and their attribution to global warming can be made with *high confidence*, despite the relatively short time frame of most observations (Figure 4-4).

Shrub expansion and height changes are particularly important because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm et al., 2005; Lawrence et al., 2007; Bonfils et al., 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III et al., 2005; Blok et al., 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils et al., 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi et al., 2007; Bonfils et al., 2012).

The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid long-distance dispersal to areas reinitialized by burning (Epstein et al., 2007; Goetz et al., 2011). When already present at the boreal-tundra ecotone, shrub and tree species show increased productivity with warmer conditions (Devi et al., 2008; Andreu-Hayles et al., 2011; Elmendorf et al., 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack et al., 2011; Rocha and Shaver, 2011), but also increase active layer depth during summer months (Racine et al., 2004; Liljedahl et al., 2007; Jorgenson et al., 2010), produce landforms associated with thawing of ice-rich permafrost, and can create conditions that alter vegetation succession (Racine et al., 2004; Lantz et al., 2009; Higuera et al., 2011).

It is *virtually certain* that the area of NH permafrost will continue to decline over the first half of the 21st century (see WGI AR5 Chapter 12) in all RCP scenarios (Figure 4-9; Caesar et al., 2013; Koven et al., 2013). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, the permafrost area is projected to stabilize at a level approximately 20% below the 20th century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550 ppmv by the mid-21st century, the simulations that extend beyond 2100 show permafrost continuing to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, the permafrost area is simulated to approach zero by the middle of the 22nd century in

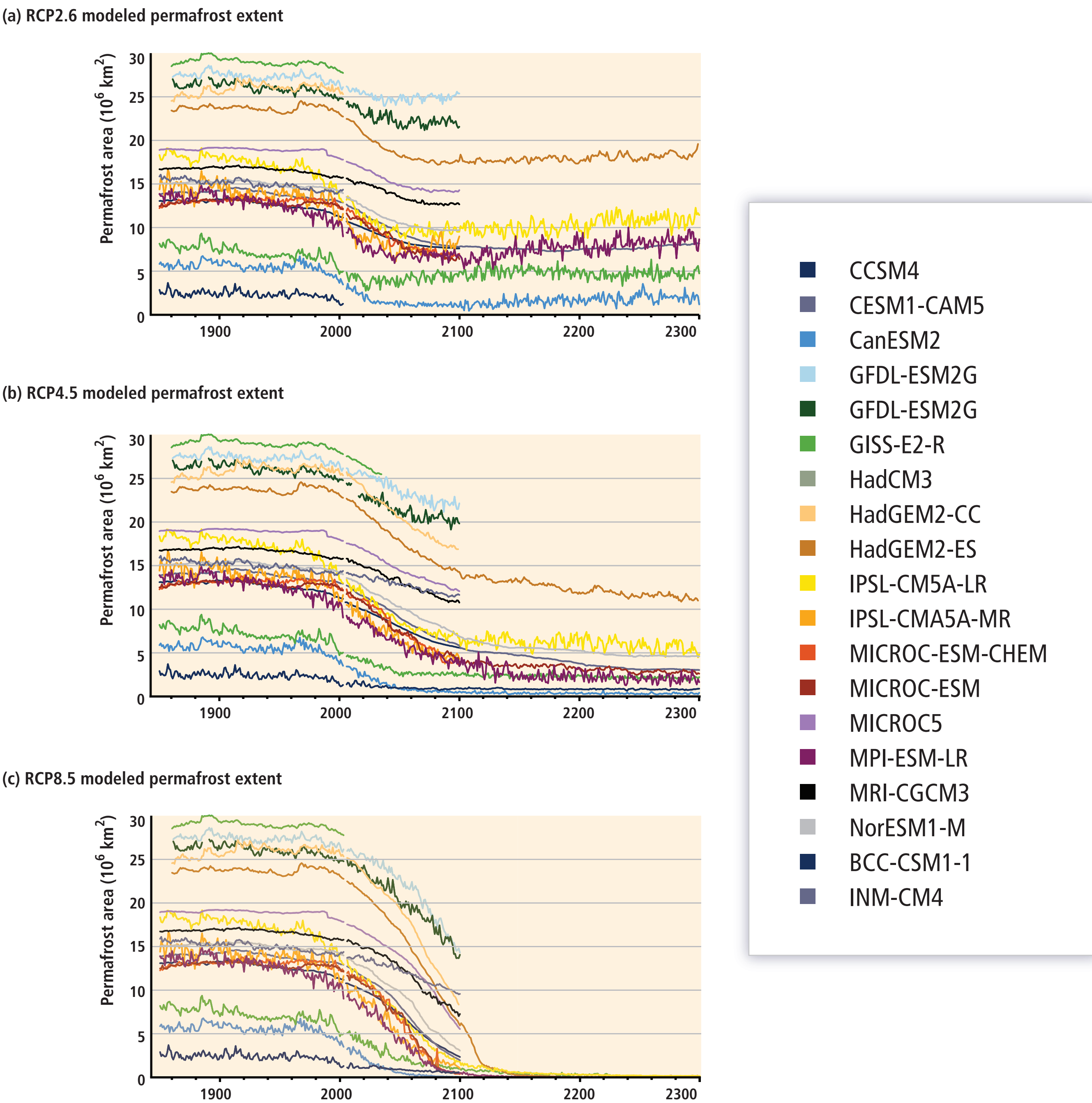

Figure 4-9 | CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3 m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850–2005) and projected (2005–2100 or 2300) simulations for (a) Representative Concentration Pathway 2.6 (RCP2.6), (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is 15 × 10^6 km^2. (Based on Koven et al., 2013, with analysis extended to 2300 following Caesar et al., 2013).

simulations that extend beyond 2100. RCP8.5 simulations that ended at 2100 showed continued permafrost decline in the late 21st century, although at slower rates in some cases as the remaining permafrost area decreases (Figure 4-9.).

Frozen soils and permafrost currently hold about 1700 PgC, more than twice the carbon than the atmosphere, and thus represent a particularly large vulnerability to climate change (i.e., warming) (see WGI AR5 Chapter 6). Although the Arctic is currently a net carbon sink, continued warming will act to turn the Arctic to a net carbon source, which will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (*high confidence*; Schuur et al., 2008, 2009; Maslin et al., 2010; McGuire et al., 2010; O'Connor et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapter 6 for detailed treatment of biogeochemistry, including feedbacks). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire et al., 2010; O'Donnell et al., 2011). The rapid retreat of snow cover and resulting spread of shrubs and trees into areas currently dominated by tundra has begun, and will continue to serve

Box 4-4 | Boreal-Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader Arctic region are consistent with Earth System Model (ESM) predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-10). Until now, these changes have been gradual shifts across temperature and moisture gradients, rather than abrupt. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the Earth, due at least in part to Arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman et al., 2005; Post et al., 2009; Peng et al., 2011; Elmendorf et al., 2012) as well as from satellite observations (Goetz et al., 2007; Beck, P.S.A. et al., 2011; Xu et al., 2013) and captured in ESMs (McGuire et al., 2010).

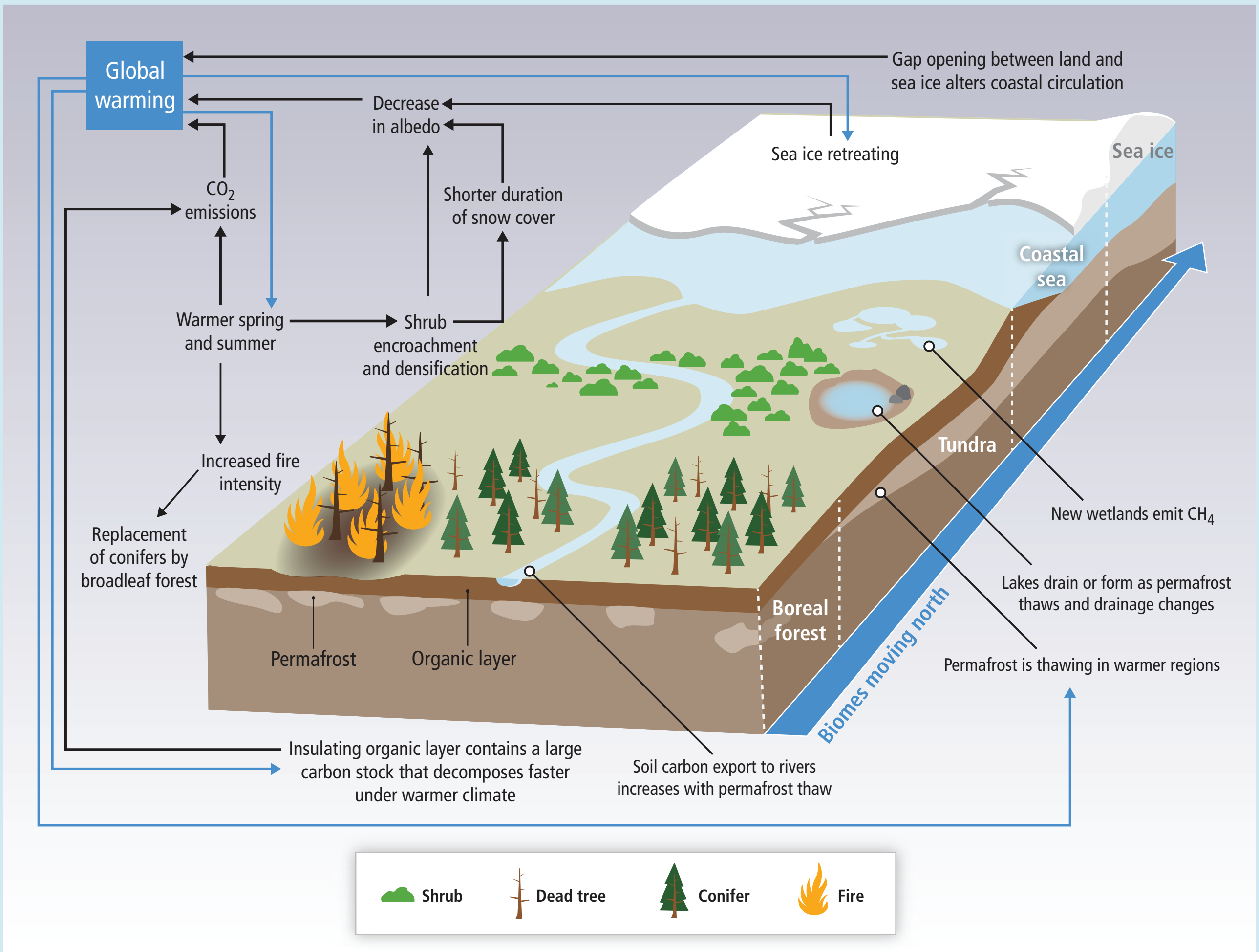

Figure 4-10 | Tundra–boreal biome shift. Earth System Models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra–forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing, and methane emissions, with net feedbacks to additional climate change.

Continued next page →

Box 4-4 (continued)

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, can be facilitated by more rapid shifts associated with fire disturbance where it can occur (Mack et al., 2008; Johnstone et al., 2010; Roland et al., 2013). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Choat et al., 2012; Ma et al., 2012; Anderegg et al., 2013a). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by long distance dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova et al., 2009; Brown, 2010; Hampe, 2011). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modeling studies, which are often poorly constrained by observations.

as a positive feedback accelerating high-latitude warming (Chapin III et al., 2005; Bonfils et al., 2012).

There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing, and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter et al., 2010; Stirling and Derocher, 2012), and it is expected that the populations of other Arctic animals will be affected dramatically by climate change, often in complex but potentially dramatic ways (e.g., Post et al., 2009; Sharma et al., 2009; Gallant et al., 2012; Gilg et al., 2012; Post and Brodie, 2012; Gauthier et al., 2013; Nielsen and Wall, 2013; Prost et al., 2013; White et al., 2013). Simple niche-based or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to ongoing climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline, and drying of soils are already causing a large increase in mountain forest mortality and wildfire, plus other ecosystem impacts (e.g., Westerling et al., 2006; Crimmins et al., 2009; van Mantgem et al., 2009; Pederson et al., 2010; Muhlfeld et al., 2011; Brusca et al., 2013; Williams et al., 2013), and disturbance will continue to be an important agent of climate-induced change in this region (Littell et al., 2010). Globally, tree line altitude appears to be changing, although not always in simple ways (Harsch et al., 2009; Tingley et al., 2012) and may sometimes be due to factors not related to climate change. Responses to climate change in high-altitude ecosystems are taking place in Africa, Asia, Europe, and elsewhere (Cannone et al., 2007, 2008; Yasuda et al., 2007; Lenoir et al., 2008, 2010; Britton et al., 2009; Chen et al., 2009, 2011; Cui and Graf, 2009; Normand et al., 2009; Allen, C.D. et al., 2010; Eggermont et al., 2010; Engler et al., 2011; Kudo et al., 2011; Laurance et al., 2011; Dullinger et al., 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli et al., 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried et al., 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback (e.g., Tibet; Cui and Graf, 2009).

4.3.3.5. Highly Human-Modified Systems

About a quarter of the land surface is now occupied by ecosystems highly modified by human activities. In this section we assess the vulnerability to climate change only of those modified systems not dealt with elsewhere, that is, excluding agriculture (Chapter 7), freshwater fisheries (Chapter 3), and urban areas (Chapter 8).

4.3.3.5.1. Plantation forestry

Plantation forests are established through afforestation or reforestation, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010). They differ from natural or semi-natural forests (Section 4.3.3.1) by generally being even-aged, having a reduced species diversity (sometimes of non-native species), and being dedicated to the production of timber, pulp, and/or bioenergy. Plantation forests contribute 7% to the global forest area (FAO, 2010), an increase of 5 million hectares between 2000 and 2010 (FAO, 2010). Most recent plantations have been established by afforestation of non-forest areas in the tropics and subtropics and some temperate regions, particularly China (Kirilenko and Sedjo, 2007; FAO, 2010). Afforestation usually results in net CO_2 uptake from the atmosphere (Canadell and Raupach, 2008; Van Minnen et al., 2008) but does not necessarily result in a reduction in global warming (Bala et al., 2007; see Section 4.3.4.5).

Growth rates in plantation forests have generally increased during the last decades but the variability is large. In forests that are not highly water limited, increased growth is consistent with higher temperatures and extended growing seasons. As in the case of forests in general, clear attribution is difficult because of the interaction of multiple environmental drivers as well as changes in forest management (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe much of the increase has been attributed to recovery following previously more intense harvesting (Ciais et al., 2008; Lindner et al., 2010).

Several studies using forest yield models suggest future increases in forest production (Kirilenko and Sedjo, 2007). These results may overestimate the positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). The effects of disturbances such as wildfires, forest pests, pathogens, and windstorms, which are major drivers of forest dynamics, are poorly represented in the models (Loustau, 2010; see also Section 4.3.3.1 and Box 4-2). The results from different models often differ substantially both regarding forest productivity (e.g., Sitch et al., 2008; Keenan et al., 2011) and potential species ranges (see Section 4.3.3.1.2). Decreased forest production is expected in already dry forest regions for which further drying is projected, such as the southwestern USA (Williams, A.P. et al., 2010). Extreme drying may also decrease yields in forests currently not water limited (e.g., Sitch et al., 2008; see Section 4.3.3.1). Plantations in cold-limited areas could benefit from global warming, provided that increased fires, storms, pests, and pathogens do not outweigh the potential direct climate effects on tree growth rates.

Low species diversity (and low genetic diversity within species where clones or selected provenances are used) renders plantation forests less resilient to climate change than natural forests (e.g., Hemery, 2008). Choosing provenances that are well adapted to current climates but pre-adapted to future climates is difficult because of uncertainties in climate projections at the time scale of a plantation forest rotation (Broadmeadow et al., 2005). How forest pests and pathogens will spread as a result of climate change and other factors is highly uncertain. New pathogen-tree interactions may arise (e.g., Brasier and Webber, 2010). Adaptive management can decrease the vulnerability of plantation forests to climate change (Hemery, 2008; Bolte et al., 2009; Seppälä, 2009; Dale et al., 2010). For example, risk spreading by promoting mixed stands, containing multiple species or provenances, combined with natural regeneration (Kramer et al., 2010), has been advocated as an adaptation strategy for temperate forests (Hemery, 2008; Bolte et al., 2010) and tropical forests (Erskine et al., 2006; Petit and Montagnini, 2006). Incomplete knowledge of the ecology of tropical tree species and little experience in managing mixed tropical tree plantations remains a problem (Hall et al., 2011). Especially at the equator-ward limits of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson et al., 2008; Bolte et al., 2010).

4.3.3.5.2. Bioenergy systems

The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation and energy security policies (Kirilenko and Sedjo, 2007). WGIII AR5 Chapter 7 addresses the potential of bioenergy as a climate mitigation strategy. The vulnerability of bioenergy systems to climate change is similar to that of plantation forestry (Section 4.3.3.5.1) or food crops (Section 7.3): in summary, they remain viable in the future in most but not all locations, but their viability is increasingly uncertain for high levels of climate change (Haberl et al., 2011). Oliver, R.J. et al. (2009) suggested that rising CO_2 might contribute to increased drought tolerance in bioenergy crops (because it leads to improved plant water use efficiency).

The unintended consequences of large-scale land use changes driven by increasing bioenergy demand are addressed in Section 4.4.4.

4.3.3.5.3. Cultural landscapes

Cultural landscapes are characterized by a long history of human-nature interactions, which results in a particular configuration of species and landscape pattern attaining high cultural significance (Rössler, 2006). Examples are grassland or mixed agriculture landscapes in Europe, rice landscapes in Asia (Kuldna et al., 2009), and many others across the globe (e.g., Rössler, 2006; Heckenberger et al., 2007). Such landscapes are often agricultural, but we deal with them here because their perceived value is only partly in terms of their agricultural products.

It has been suggested that protected area networks (such as Natura 2000 in Europe, which includes many cultural landscape elements) be adjusted to take into account climate change (Bertzky et al., 2010). Conserving species in cultural landscapes (e.g., EU Council, 1992) generally depends on maintaining certain types of land use. Doing so under climate change requires profound knowledge of the systems and species involved, and conservation success so far has been limited (see Thomas et al., 2009, for a notable exception). Understanding the relative importance of climate change and land management change is critical (Settele and Kühn, 2009). To date land use changes have been the most obvious driver of change (Nowicki et al., 2007); impacts have been attributed to climate change (with *low* to *medium confidence*) in only a few examples (Devictor et al., 2012). Even in these, combined land use-climate effects explain the pattern of observed threats better than either alone (Schweiger et al., 2008, 2012; Clavero et al., 2011).

There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes that there is *very low confidence* that we can attribute these observations to climate change (Figure 4-4).

4.3.3.5.4. Urban ecosystems

Although urban areas (for definition see Section 8.1.2) cover only 0.5% of the Earth's land surface (Schneider et al., 2009), more than half of humanity lives there (increasing annually by 74 million people; UN DESA Population Division, 2012) and they harbor a large variety of species (McKinney, 2008). The frequency and magnitude of warm days and nights (heat waves) is *virtually certain* to increase globally in the future

Frequently Asked Questions

FAQ 4.5 | Why does it matter if ecosystems are altered by climate change?

Ecosystems provide essential services for all life: food, life-supporting atmospheric conditions, drinkable water, as well as raw materials for basic human needs such as clothing and housing. Ecosystems play a critical role in limiting the spread of human and non-human diseases. They have a strong impact on the weather and climate itself, which in turn impacts agriculture, food supplies, socioeconomic conditions, floods, and physical infrastructure. When ecosystems change, their capacity to supply these services changes as well—for better or worse. Human well-being is put at risk, along with the welfare of millions of other species. People have a strong emotional, spiritual, and ethical attachment to the ecosystems they know, and the species they contain.

By "ecosystem change" we mean changes in some or all of the following: the number and types of organisms present; the ecosystem's physical appearance (e.g., tall or short, open or dense vegetation); and the functioning of the system and all its interactive parts, including the cycling of nutrients and productivity. Though in the long term not all ecosystem changes are detrimental to all people or to all species, the faster and further ecosystems change in response to new climatic conditions, the more challenging it is for humans and other species to adapt to the new conditions.

(IPCC, 2012); this trend is higher in urban than in rural areas (McCarthy et al., 2010). Heavy rainfall events are also projected to increase (IPCC, 2012), and although the hydrological conditions in urban areas make them prone to flooding (*medium confidence*), there is *limited evidence* that they will be over-proportionally affected. It is very likely that sea level rise in the future will contribute to flooding, erosion, and salinization of coastal urban ecosystems (IPCC, 2012). Climate change is projected to increase the frequency of landslides (UN-HABITAT, 2011). Climate change impacts on urban ecosystems and biodiversity have received comparatively little attention, with water availability being an exception (Hunt and Watkiss, 2011). Changes in water availability and quality due to changes in precipitation, evaporation, or in salinity regimes will especially affect urban freshwater ecosystems (Hunt and Watkiss, 2011). As in other ecosystems, climate change will lead to a change in species composition, the frequency of traits, and ecosystem services from urban ecosystems. Knapp, S. et al. (2008) found that trait composition of plant communities changes during urbanization toward adaptive characteristics of dry and warm environments (see also Sections 4.2.4.6 and 4.3.2.5). Urban areas are one of the main points of introduction of alien species (e.g., for plants through urban gardening; Knapp, S. et al., 2012). Increased damage by phytophagous insects to plants in urban environments is anticipated (Kollár et al., 2009; Lopez-Vaamonde et al., 2010; Tubby and Webber, 2010; see also Section 8.2.4.5).

4.3.4. Impacts on Key Ecosystem Services

Ecosystem services are the benefits that people derive from ecosystems (see Glossary). Many ecosystem services are plausibly vulnerable to climate change. The Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2003) recognizes *provisioning services* such as food (Chapter 7), fiber (Section 4.3.4.2), bioenergy (Section 4.3.4.3), and water (Chapter 3); *regulating services* such as climate regulation (Section 4.3.4.5), pollination, pest and disease control (Section 4.3.4.4), and flood control (Chapter 3); *supporting services* such as primary production (Section 4.3.2.2) and nutrient cycling (Section 4.2.4.2, and indirectly Section 4.3.2.3); and *cultural services*, including recreation and aesthetic and spiritual benefits (Section 10.6). Section 4.3.4.1 focuses on ecosystem services not already covered in the sections referenced above.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing (1) shifts in habitat distribution that are not followed by species, (2) shifts in species distributions that move them outside of their preferred habitats, and (3) changes in habitat quality (Dullinger et al., 2012; Urban et al., 2012). Climate change impacts on habitats for biodiversity are already occurring (see the polar bear example in Section 28.2.2.1.3) but are not yet a widespread phenomenon. Models of future climate change-induced shifts in the distribution of ecosystems suggest that many species could be outside of their preferred habitats within the next few decades (Urban et al., 2012; see Sections 4.3.2.5, 4.3.3, and Figure 4-1).

Hole et al. (2009) report that the majority of African birds would have to move large distances (up to several hundred kilometers) over the next 60 years (under SRES B2a), resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa). To reach suitable climates they will have to migrate across unfavorable habitats. Many may continue to find suitable climate within the protected area network, but will be forced to cope with new habitat constraints (Hole et al., 2009). Araujo et al. (2011) estimate that by 2080 approximately 60% (58 ± 2.6%) of plants and vertebrate species will no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats (based on SRES A1, A2, B1, and A1FI scenarios). Wiens et al. (2011) project similar effects in the western USA (until the year 2069, based on SRES A2 scenarios), but also find that climate change may open up new opportunities for protecting species in areas where climate is currently unsuitable. In some cases climate change may allow species to move into areas of lower current or future land use pressure including protected areas (Bomhard et al., 2005). These studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species (see Sections 4.4.2.2, 4.4.2.3).

In the long term, some habitat types may disappear entirely due to climate change (see Section 4.3.3 and Figure 4-1). Climates are projected to occur in the future that at least in some features do not represent climates that existed in the past (Williams, J.W. et al., 2007; Wiens et al., 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (Section 4.2.3). The impacts of habitat change on species abundance and extinction risk are difficult to evaluate because at least some species are able to adapt to novel habitats (Prugh et al., 2008; Oliver, T. et al., 2009). The uncertainty in habitat specificity is one reason why quantitative projection of changes in extinction rates is difficult (Malcolm et al., 2006).

The effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. Several recent studies indicate that climate change may have altered habitat quality already and will continue to do so (Iverson et al., 2011; Matthews et al., 2011). For example, decreasing snowfall in the southwestern USA has negatively affected the habitat for songbirds (Martin and Maron, 2012).

4.3.4.2. Timber and Pulp Production

In most areas with forest plantations, forest growth rates have increased during the last decades, but the variability is large, and in some areas production has decreased (see Section 4.3.3.1). In forests that are not highly water limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe a reduction in harvesting intensity has contributed (Ciais et al., 2008; Lindner et al., 2010).

Forest yield models project future increases in forest production under climate change, perhaps over optimistically (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). Using a model that accounts for fire effects and insect damage, Kurz et al. (2008) showed that the Canadian forest sector may have transitioned from a sink to a source of carbon.

4.3.4.3. Biomass-Derived Energy

Bioenergy sources include traditional forms such as wood and charcoal from forests (see Section 4.3.3.1) and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel, and plantations of bioenergy crops. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less developed parts of the world, such as Africa, and retain a niche in developed countries. Generally, potentials of bioenergy production under climate change may be high, but are very uncertain (Haberl et al., 2011).

4.3.4.4. Pollination, Pest, and Disease Regulation

It can be inferred that global change will result in new communities (Gilman et al., 2010; Schweiger et al., 2010). As these will have had little opportunity for coevolution, changes in ecological interactions, such as shifts in herbivore diets, the range of prey of predators, or in pollination networks are to be expected (Tylianakis et al., 2008; Schweiger et al., 2012). This may result in temporarily reduced effectiveness of the "regulating services," which generally depend on species interactions (Montoya and Raffaelli, 2010). Burkle et al. (2013) show that the loss of species reduces co-occurrence of interacting species and thus reduces ecosystem functions based on them.

Climate change tends to increase the abundance of pest species, particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced by climate change, for example, through a longer warm season during which to breed, and indirectly, for example, through the quality of food plants (Jamieson et al., 2012) or via changes in their natural enemies (predators and parasitoids). Insects have well-defined temperature optima; warming toward the optimum leads to increased vitality and reproduction (Allen, C.D. et al., 2010). Mild winters in temperate areas promote pests formerly controlled by frost sensitivity. For the vast majority of indirect effects, information is scarce. Further assessments of climate change effects on pest and disease dynamics are found in Sections 7.3.2.3 for agricultural pests and 11.5.1 for human diseases.

Climate change has severe negative impacts on pollinators (including honeybees) and pollination (Kjøhl et al., 2011) (*medium confidence*). After land use changes, climate change is regarded as the second most relevant factor responsible for the decline of pollinators (Potts et al., 2010; for other factors see Biesmeijer et al., 2006; Brittain et al., 2010a,b). The potential influence of climate change on pollination can be manifold (compare Hegland et al., 2009; Schweiger et al., 2010; Roberts et al., 2011). There are a few observational studies, which mostly relate to the phenological decoupling of plants and their pollinators (Gordo and Sanz, 2005; Bartomeus et al., 2011). While Willmer (2012) states, based on experimental studies, that phenological effects may be less important than has been suggested, an analysis of phenological observations in plants by Wolkovich et al. (2012) shows that experimental data on phenology may grossly underestimate the actual phenological shifts.

Le Conte and Navajas (2008) state that the generally observed decline in honeybees is a clear indication of an increasing susceptibility to global change phenomena, with pesticide application, new diseases, and stress (and a combination of these) as the most relevant causes. Climate change may contribute by modifying the balance between honeybees and their environment (including exposure or susceptibility to diseases). Honeybees show a high capacity to adjust to a variety of environments; their high genetic diversity should allow them to also cope with climatic change (Bartomeus et al., 2011). The preservation of genetic variability within honeybees is regarded as a key adaptation strategy for pollination services (Le Conte and Navajas, 2008).

4.3.4.5. Moderation of Climate Change, Variability, and Extremes

The focus of this section is on processes operating at regional to global scales, rather than the well-known microclimatic benefits of ecosystems in smoothing day-night temperature variations and providing local evaporative cooling. In the decade 2000–2009, the global net uptake of CO_2 by terrestrial ecosystems was a large fraction of the anthropogenic CO_2 emissions to the atmosphere from all sources, reducing the rate of climate change proportionately (Section 4.3.2.3; WGI AR5 Section 6.3.2).

Afforestation or reforestation are potential climate mitigation options (Van Minnen et al., 2008; Vaughan and Lenton, 2011; Fiorese and Guariso, 2013; Singh et al., 2013) but, as discussed in Section 4.2.4.1, the net effect of afforestation on the global climate is mixed and context dependent. Wickham et al. (2012) found significant positive correlations between the average annual surface temperature and the proportion of forest in the landscape and conclude that the climate benefit of temperate afforestation is unclear. Where low-albedo forest canopies replace higher-albedo surfaces such as soil, grassland, or snow, the resultant increase in net radiative forcing counteracts the benefits of carbon sequestration to some degree (Arora and Montenegro, 2011). Where the cloud cover fraction is low and the albedo difference is large, that is, outside the humid tropics, the long-term net result of afforestation can be global warming (Bala et al., 2007; Bathiany et al., 2010; Schwaiger and Bird, 2010). Accounting for changes in albedo and indirect greenhouse effects are not currently required in the formal rules for quantifying for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum et al., 2012). There are potential negative trade-offs between afforestation for climate mitigation purposes and other ecosystem services, such as water supply (Jackson et al., 2005) and biodiversity maintenance (CBD, 2012; Russell et al., 2012).

It has been suggested (Ridgwell et al., 2009) that planting large areas of crop varieties with highly reflective leaves could help mitigate global change. Model analyses indicate this "geo-engineering" strategy would be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes. Measurements of leaf albedo in major crops show that the current range of variability is insufficient to make a meaningful difference to the global climate (Doughty et al., 2011).

4.4. Adaptation and Its Limits

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see Glossary under adaptation) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit et al., 2000)—also called "spontaneous adaptation" (Smit et al., 2007). In the context of human systems it is sometimes called "coping capacity." The capacity for autonomous adaptation is part of resilience but is not exactly synonymous (Walker et al., 2004).

All social and ecological systems have some capacity for autonomous adaptation. Ecosystems that have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability that they have experienced in the past. An environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft et al., 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology, or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, through in- or out-migration or local extinction.

The ability to project impacts of climate change on ecosystems is complicated by the potential for species to adapt. Adaptation by individual species increases their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin et al., 2007). It may also affect their interactions with other species, leading to disruption of the biotic community (Visser and Both, 2005).

4.4.1.1. Phenological

Changes in phenology are occurring in many species and locations (Section 4.3.2.1). Further evidence since AR4 shows how this can be an adaptation to climate change, but also the limits to phenological adaptation. An organism's phenology is typically highly adapted to the climate seasonality of the environment in which it evolved. Species unable to adjust their phenological behavior will be negatively affected, particularly in highly seasonal habitats (Both et al., 2010).

Moreover, the phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species, and pollinators. Systematic cross-taxa studies indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook et al., 2008; Thackeray et al., 2010). If adaptation is insufficiently rapid or coordinated between interdependent species, disruption of ecological features such as trophic cascades, competitive hierarchies, and species coexistence is inferred to result (Nakazawa and Doi, 2012). Lack of coordination can occur if one of the species is cued to environmental signals that are not affected by climate change, such as day length (Parmesan, 2006). Increasing temperatures may bring species either more into or out of synchrony, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more toward a loss of synchrony (Thackeray et al., 2010).

Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. For example, bird breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100

European migratory bird species, those that advanced their arrival date showed stable or increasing populations between 1990 and 2000, while those that did not adjust their arrival date on average showed declining populations (Møller et al., 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) between 1987 and 2003, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, but not in areas with a later food peak that could still be exploited by early breeding birds (Both et al., 2006). However, compensating processes can exist: for example, in a 4-decade study of great tits (*Parus major*), breeding populations were buffered against phenological mismatch due to relaxed competition between individual fledglings (Reed et al., 2013). Between 1970 and 1990, changes in migration date did not predict changes in population sizes (Møller et al., 2008).

Bird breeding can also be affected by phenological shifts in competing species and predators. Between 1953 and 2005 in southwestern Finland, the onset of breeding of the resident great tit *Parus major* and the migratory pied flycatcher (*Ficedula hypoleuca*) became closer to each other, increasing competition between them (Ahola et al., 2007). The edible dormouse (*Glis glis*), a nest predator, advanced its hibernation termination by -8 days per decade in the Czech Republic between 1980 and 2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four surveyed bird species (Adamik and Kral, 2008).

Plant-insect interactions have also been observed to change. In Illinois, USA, the pattern of which plants were pollinated by which bees were altered by differing rates of phenological shifts and landscape changes over 120 years, with 50% of bee species becoming locally extinct (Burkle et al., 2013). Increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) in the Netherlands was linked to increasing spring temperatures but unchanging winter temperatures (van Asch and Visser, 2007). Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer*), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors including day length and food quality may complicate this prediction (Kollberg et al., 2013). In North America, the spruce budworm (*Choristaneura fumiferana*) lays eggs with a wide range of emergence timings, so the population as a whole is less sensitive to changing phenology of host trees (Volney and Fleming, 2007).

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The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, since the relative importance of cues can change (Cook et al., 2012b). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky Mountains to frost because plants begin flowering earlier as a result of earlier snowmelt (Inouye, 2008).

It has been suggested that shorter generation times give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux et al., 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time had only limited influence on adaptation rates (Thackeray et al., 2010).

There is *high confidence* (*much evidence*, *medium agreement*) that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle.

4.4.1.2. Evolutionary and Genetic

Since AR4 there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution." Evolution can occur through many mechanisms, including selection of existing genes or genotypes within populations, hybridization, mutation, and selection of new adaptive genes and perhaps even through epigenetics (Chevin et al., 2010; Chown et al., 2010; Lavergne et al., 2010; Paun et al., 2010; Hoffmann and Sgro, 2011; Anderson et al., 2012a; Donnelly et al., 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang et al., 2013). Mechanisms such as selection of existing genes and genotypes, hybridization, and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take many tens of generations. This means that species with very fast life cycles, for example, bacteria, should in general have greater capacity to respond to climate change than species with long life cycles, such as large mammals and trees. There is a paucity of observational or experimental data that can be used for detection and attribution of recent climate effects on evolution.

4.4.1.2.1. Observed evolutionary and genetic responses to rapid changes in climate

There is a small but growing body of observations supporting the AR4 assessment that some species may have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants: Franks and Weis, 2008; Hill et al., 2011; Anderson et al., 2012b; vertebrates: Ozgul et al., 2010; Phillimore et al., 2010; Husby et al., 2011; Karell et al., 2011; insects: Buckley et al., 2012; van Asch et al., 2012). Karell et al. (2011) found increasing numbers of brown genotypes of the tawny owl (*Strix aluco*) in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the white genotype. Earlier spawning by the common frog (*Rana temporaria*) in Britain could be attributed largely to local genetic adaptation to increasing spring temperatures (Phillimore et al., 2010). Using a combination of models and observations, Husby et al. (2011) have built a case for detection and attribution of genetic adaptation in an insectivorous bird and in an herbivorous insect that has tracked warming-related changes in the budburst timing of its host tree (van Asch et al., 2012). In contrast, many species appear to be maladapted to changing climates, in part because factors such as limited existing genetic variation, weak heritability of adaptive traits, or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen et al., 2011; Ketola et al., 2012; Merilä, 2012; Mihoub et al., 2012). Most studies of rapid evolution suffer from methodological weaknesses, making it difficult to demonstrate clearly a genetic basis underlying observed phenotypic responses to environmental change (Gienapp et al., 2008; Franks and Hoffmann, 2012; Hansen et al., 2012; Merilä, 2012). Rapid advances in quantitative genetics, genomics, and phylogenetics, combined with recent progress on conceptual frameworks, will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis, C.C. et al., 2010; Salamin et al., 2010; Hoffmann and Sgro, 2011). In sum, there are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* for detection and attribution across all species; Figure 4-4).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is evidence that environmental niches are conserved for some species under some conditions (plants: Petitpierre et al., 2012; birds: Monahan and Tingley, 2012; review: Peterson et al., 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following changes in climate (Broennimann et al., 2007; Angetter et al., 2011; Konarzewski et al., 2012; Leal and Gunderson, 2012; Lavergne et al., 2013). The paleontological record provides insight into evolutionary responses in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there are insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson et al., 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Hegarty, 2012; Soliani et al., 2012). There is new evidence that epigenetic mechanisms, such as DNA methylation, could allow very rapid adaptation to climate (Paun et al., 2010; Zhang et al., 2013).

4.4.1.2.2. Mechanisms mediating rapid evolutionary response to future climate change

Studies of genetic variability across species ranges, and models that couple gene flow with spatially explicit population dynamics, suggest counterintuitive responses to climate change. Too much or too little gene flow to populations at range margins can create fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle et al., 2010; Hill et al., 2011). Conversely, there is evidence from experiments, models, and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization is complicated by the interactions between local adaptation, gene flow, population dynamics, and species interactions (Bridle et al., 2010; Norberg et al., 2012).

Substantial progress has been made since AR4 in developing models for exploring whether genetic adaptation is fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to slightly attenuate negative impacts of future climate change (Kuparinen et al., 2010; Kremer et al., 2012). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected climate change, owing to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp et al. (2013) found that modeled avian breeding times tracked climate change, only at low to moderate rates of change. For a herbivorous insect with an even faster life cycle, van Asch et al. (2007, 2012) predicted that rapid evolution of the phenological response should have allowed it to track recent warming, which it has.

More broadly, models suggest that species with short generation times (1 year or less) potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change given large enough present-day populations, but species with longer generation times or small populations could be at risk of extinction at moderate to high rates of climate change (Walters et al., 2012; Vedder et al., 2013). Recent experimental and theoretical work on "evolutionary rescue" shows that long-term avoidance of extinction through genetic adaptation to hostile environments is possible, but requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size, and range contractions over many generations before population recovery (Bell, 2013; Schiffers et al., 2013).

Model-based projections must be viewed with considerable caution because there are many evolutionary and ecological mechanisms not accounted for in most models that can either speed up or inhibit heritable adaptation to climate change (Cobben et al., 2012; Norberg et al., 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of greater maladaptation to climate change, resulting in rapid population declines (Hendry and Gonzalez, 2008; Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change. High plasticity in the face of climate change that has low fitness costs can greatly improve the odds of adaptation; however, plasticity with high costs leads to only modest amounts of adaptation (Chevin et al., 2010).

AR4 concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)" (Fischlin et al., 2007). Work since then provides a similar, but more nuanced view of rapid evolution in the face of future climate change. The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism, and models showing limited adaptive capacity in species with long generation times all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines, and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in Section 4.3.2.5. It is anticipated that the observed movement of species—individually and collectively—will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-5). Second, the ecosystem interactions can remain intact only if all parts of the ecosystem migrate simultaneously and at the same rate. Third, the contemporary landscape and inland water systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements, and dams. Mountain ecosystems are less constrained by these factors than flat-land ecosystems, but have additional impediments for species already close to the top of the mountain.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate intervention with the intent of increasing the capacity of the target organism, ecosystem, or socio-ecological system to survive and function at an acceptable level in the presence of climate change. It is also known as "planned adaptation" (Smit et al., 2007). This chapter focuses less on the adaptation of people, human communities, and infrastructure, as they are the topics of Chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. Intervention in this context means a range of actions, including ensuring the presence of suitable habitat and dispersal pathways; reducing non-climate stressors; and physically moving organisms and storing and establishing them in new places. In addition to the other approaches assessed in this section, "Ecosystem-Based Adaptation" (see Box CC-EA) provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaptation. Note that there are risks associated with all forms of human-assisted adaptation (see Section 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, as the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris et al., 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). Protective and restorative actions aimed at increasing resilience can also be a cost-effective means as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change and may have other social, economic, and cultural benefits. This is part of "ecosystem-based adaptation" (Colls et al., 2009; Box CC-EA).

4.4.2.2. The Size, Location, and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that most biodiversity exists outside rather than in protected areas and this between-protected area matrix is as important; that it is usually cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah et al., 2007); and that the existing protected area network will still have utility in future climates, even though it may contain different species (Thomas et al., 2012).

Hickler et al. (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century climate change a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new areas that need to be added to the existing protected area network to ensure future representativeness is situation specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux et al., 2008); regional scale planning is more effective than treating each local case independently because it is the network of habitats and protected areas that confers resilience rather than any single element (Heller and Zavaleta, 2009); and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009). Dunlop et al. (2012) assessed the implications of climate change for biodiversity conservation in Australia and found many opportunities to facilitate the natural adaptation of biodiversity, including expanding the network of protected areas and restoring habitat at a large scale.

4.4.2.3. Landscape and Watershed Management

The need to include climate change into the management of vulnerable ecosystems is explicitly included in the strategic goals of the Convention on Biological Diversity. Oliver et al. (2012b) developed decision trees based on three scenarios: (1) *adversely sensitive*, where areas within the species current geographical range will become climatically unsuitable with a changing climate; (2) *climate overlap*, where there are areas that should remain climatically suitable within the species' range; and (3) *new climatic space*, which refers to areas outside of the current range that are projected to become suitable. Heller and Zavaleta (2009) reviewed recommendations in the published literature and argue that the majority of them, such as increase habitat heterogeneity of sites and connectivity of habitats across landscapes, lack sufficient specificity to ensure the persistence of many species and related ecosystem services to ongoing climate change. To date, recommendations are overwhelmingly focused on ecological data, neglecting social science insights. Few resources or capacity exist to guide adaptation planning processes at any scale.

Frequently Asked Questions

FAQ 4.6 | Can ecosystems be managed to help them and people to adapt to climate change?

The ability of human societies to adapt to climate change will depend, in large measure, on the management of terrestrial and inland freshwater ecosystems. A fifth of global human-caused carbon emissions today are absorbed by terrestrial ecosystems; this important carbon sink operates largely without human intervention, but could be increased through a concerted effort to reduce forest loss and to restore damaged ecosystems, which also co-benefits the conservation of biodiversity.

The clearing and degradation of forests and peatlands represents a source of carbon emissions to the atmosphere which can be reduced through management; for instance, there has been a three-quarters decline in the rate of deforestation in the Brazilian Amazon in the last 2 decades. Adaptation is also helped through more proactive detection and management of wildfire and pest outbreaks, reduced drainage of peatlands, the creation of species migration corridors, and assisted migration.

Climate-induced impacts to hydrological and thermal regimes in freshwater systems can be offset through improved management of environmental flow releases from reservoirs (Arthington et al., 2006, 2010 and references therein; Poff et al., 2010). Protection and restoration of riparian vegetation in small stream systems provide an effective strategy to moderate temperature regimes and offset warming, and protect water quality for downstream ecosystems and water supply areas (Davies, 2010; Capon et al., 2013).

General principles for management adaptations were summarized from a major literature review by West et al. (2009). They suggest that in the context of climate change, successful management of natural resources will require cycling between "managing for resilience" and "managing for change." This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, principles to facilitate adaptation include (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

Steenberg et al. (2011) simulated the effect on adaptive capacity of three variables related to timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives. Manipulation of vegetation composition and stand structure has been proposed as a strategy for offsetting climatic change impacts on wildfires in Canada. Large areas of boreal forests are currently being harvested and there may be opportunities for using planned manipulation of vegetation for management of future wildfire risks. This management option could also provide an additional benefit to the use of assisted species migration because the latter would require introducing non-flammable broadleaves species into forests that are otherwise highly flammable (Girardin et al., 2013b; Terrier et al., 2013). Harvesting practices, such as partial cuts that limit the opening of the forest cover created by harvest, will be a key element to maintain diverse forest compositions and age class distributions in boreal forests. Another sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species requiring a shorter rotation (Girardin et al., 2013a).

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change (Hoegh-Guldberg et al., 2008; Vitt et al., 2010; Chmura et al., 2011; Loss et al., 2011; Ste-Marie et al., 2011). The options for management can be summarized as: (1) try to maintain or improve existing habitat or environment so that species do not have to move (e.g., Settele and Kühn, 2009); (2) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson et al., 2012); and (3) directly translocate species or genetically distinct populations within a species (Aitken et al., 2008; Hoegh-Guldberg et al., 2008; Rehfeldt and Jaquish, 2010; Loss et al., 2011; Pedlar et al., 2012). There is *low agreement* whether it is better to increase the resilience to climate change of ecosystems as they currently occur, or to enhance capacity of ecosystems to transform in the face of climate change (Richardson et al., 2009).

There is *high agreement* that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole et al., 2011; Jongman et al., 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystem-wide approach than assisted migration for individual species. However, observational and modeling studies show that increases in habitat connectivity do not always improve the population dynamics of target species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson et al., 2010; Matthiessen et al., 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg et al., 2008; Vitt et al., 2009; Willis and Bhagwat, 2009; Loss et al., 2011; Hewitt et al., 2011). The velocity of 21st century climate change and substantial habitat fragmentation in large parts of the world means that many species will be unable to migrate or adapt fast enough to keep pace with climate change (Figure 4-5), posing problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that require assisted migration could easily overwhelm funding capacity (Minteer and Collins, 2010). Decisions regarding which species should be translocated are complex and debatable, given variability among and within species and the ethical issues involved (Aubin et al., 2011; Winder, R. et al., 2011).

4.4.2.5. *Ex Situ* Conservation

Conservation of plant and animal genetic resources outside of their natural environment—in gardens, zoos, breeding programs, seed banks, or gene banks—has been widely advocated as an "insurance" against both climate change and other sources of biodiversity loss and impoverishment (Khoury et al., 2010). There are many examples of existing efforts of this type, some with global scope (e.g., Millennium Seed Bank, Svalbard Vault, Frozen Ark, Global Genome Initiative, and others; Lermen et al., 2009; Rawson et al., 2011). Knowledge of which genetic variants within a species have more potential for adaptation to climate change could help prioritize the material stored (Michalski et al., 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional, and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intraspecific variation that needs to be preserved for future viability and how much genetic bias is introduced by collecting relatively small samples from restricted locations, and then later by the selection pressures inadvertently applied during *ex situ* maintenance are unknown. Despite some documented successes, it remains uncertain whether it is always possible to reintroduce species successfully into the wild after generations of *ex situ* conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ecosystem services provided, or incur costs in order to maintain or restore the services or adapt to their decline. There are several sources of such costs: administration and assessment, implementation, and opportunity costs, including financial cost. Owing to the number of assumptions made, knowledge gaps, and recognized uncertainties, such result should be employed with caution. A systematic review of costs related to ecosystems and climate change by Rodriguez-Labajos (2013) shows that the monetary and non-monetary costs are distributed across all ecosystem service categories. It also discusses the potential and limits of monetary cost calculations, and issues of timing, trade-offs, and the unequal distribution of costs.

A comprehensive monetary estimate of the effects of climate change on ecosystem service provision is not available. The Millennium Ecosystem Assessment (2005c,d,e) included climate change among the direct drivers of ecosystems change and devoted a chapter to the necessary responses. Building on results of the IPCC, the Millennium Ecosystem Assessment offered some estimated costs of action: complying with the Kyoto protocol for industrial countries would range between 0.2 and 2% of GDP; a modest stabilization target of 450 ppm CO_2 in the atmosphere over the 21st century would range from 0.02 to 0.1% of global-average GDP per year. TEEB (2009) underlined priorities in the ecosystem service-climate change coupling (reduction targets in relation to coral reefs, forest carbon markets and accounting, and ecosystem investment for mitigation), without going in depth into analysis of the cost types involved. The Cost of Policy Inaction (COPI) Project (ten Brink et al., 2008) estimated the monetary costs of not meeting the 2010 biodiversity goals. Their model incorporates climate change, among other pressures, through an impaired quality of land, in terms of species abundance in diverse land use categories. They conclude that the cumulative losses

Frequently Asked Questions

FAQ 4.7 | What are the economic costs of changes in ecosystems due to climate change?

Climate change will certainly alter the services provided by most ecosystems, and for high degrees of change, the overall impacts are most likely to be negative. In standard economics, the value of services provided by ecosystems are known as externalities, which are usually outside the market price system, difficult to evaluate, and often ignored.

A good example is the pollination of plants by bees and birds and other species, a service that may be negatively affected by climate change. Pollination is critical for the food supply as well as for overall environmental health. Its value has been estimated globally at US$350 billion for the year 2010 (range of estimates of US$200 to 500 billion).

of welfare due to land use changes, in terms of loss of ecosystem services, could reach an annual amount of EUR 14 trillion (based on 2007 values) in 2050, which may be equivalent to 7% of projected global GDP for that year. Eliasch (2008) estimates the damage costs to forests as reaching US$1 trillion a year by 2100. The study used the probabilistic model employed by Stern (2006), which did not value effects on biodiversity or water-related ecosystem services.

The studies to date agree on the following points. First, climate change has already caused a reduction in ecosystem services that will become more severe as climate change continues. Second, ecosystem-based strategies to mitigate climate change are cost effective, although more difficult to implement (i.e., more costly) in intensively managed ecosystems such as farming lands. Third, accurately estimating the monetary costs of reduction in ecosystem services that are not marketed is difficult. The provision of monetized costs tends to sideline the non-monetized political, social, and environmental costs relevant for decision making. Finally, there is a large funding gap between the cost of actions necessary to protect ecosystem services against climate change and the actual resources available.

In addition to direct costs, further costs may result from trade-offs between services: for example, afforestation for climate mitigation and urban greening for climate adaptation may be costly in terms of water provision (Chisholm, 2010; Jenerette et al., 2011; Pataki et al., 2011). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity, and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011) but, due to the typically lower per hectare yields, may require a larger area to be dedicated to cropland. Leaving aside the contested (Searchinger et al., 2008; Plevin et al., 2010) effectiveness of biofuels as a mitigation strategy, there is evidence of their disruptive effect on food security, land tenure, labor rights, and biodiversity in several parts of the world (Obersteiner et al., 2010; Tirado et al., 2010).

4.4.4. Unintended Consequences of Adaptation and Mitigation

Actions taken within the terrestrial and freshwater system domain or in other sectors to mitigate or adapt to climate change can have unintended consequences. Some issues relevant to this section are also found in Section 14.7 and the Working Group III contribution to the AR5.

Several of the alternatives to fossil fuel require extensive use of the land surface and thus have a direct impact on terrestrial ecosystems and an indirect impact on inland water systems (Paterson et al., 2008; Turner et al., 2010). As an illustration, the RPC2.6 scenario involves both bioenergy and renewables as major components of the energy mix (Box 4-1; van Vuuren et al., 2011).

Policy shifts in developed countries favor the expansion of large-scale bioenergy production, which places new pressures on terrestrial and freshwater ecosystems (Searchinger et al., 2008; Lapola et al., 2010), either through direct use of land or water or indirectly by displacing food crops, which must then be grown elsewhere. Over the past decade there has been a global trend to reduced rates of forest loss; it is unclear if this will continue in the face of simultaneously rising food and biofuel demand (Wise et al., 2009; Meyfroidt and Lambin, 2011). The EU Renewable Energy Sources Directive is estimated to have only a moderate influence on European forests provided that the price paid by the bioenergy producers remained below US$50 to 60 per cubic meter of wood (Moiseyev et al., 2011). However, a doubled growth rate for bioenergy until 2030 would have major consequences for the global forest sector, including a reduction of forest stocks in Asia of 2 to 4% (Buongiorno et al. 2011). By 2100 in RCP2.6, bioenergy crops are projected to occupy approximately 4 million km^2, about 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risks (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive, and "natural" areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may contribute to extinction risks. Some bioenergy crops may be invasive species (Raghu et al., 2006).

Abandoned former agricultural land could be used for biomass production (McAlpine et al., 2009). However, such habitats may be core elements in cultural landscapes of high conservation value, with European species-rich grasslands often developed from abandoned croplands (Hejcman et al., 2013).

Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, for example, of amphibians (Brandão and Araújo, 2007). Reservoirs can be a sink of CO_2 but also a source of biogenic CO_2 and CH_4; this issue is discussed in WG III AR5 Section 7.8.1.

Wind turbines can kill birds and bats (e.g., Barclay et al., 2007), and inappropriately sited wind farms can negatively impact on bird populations (Drewitt and Langston, 2006). Effects can be reduced by careful siting of turbines, for example by avoiding migration routes (Drewitt and Langston, 2006). Estimating mortality rates is complex and difficult (Smallwood, 2007) but techniques are being developed to inform siting decisions and impact assessments (Péron et al., 2013). Wind farms in Europe and the USA are estimated to cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour of electricity, compared to approximately 5.2 wildlife fatalities per gigawatt-hour for nuclear and fossil-fuel power stations (Sovacool, 2009; but see Willis, C.K.R. et al., 2010). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins et al., 2012).

Large-scale solar farms could impact local biodiversity if poorly sited, but the impact can be reduced with appropriate planning (Tsoutsos et al., 2005). Solar photovoltaic installations can decrease local surface albedo, giving a small positive radiative forcing. There are some plausible local circumstances in which this may be a consideration, but in general the climate effect is estimated to be 30 times smaller than the avoided radiative forcing arising from substituting fossil fuels with PV (Nemet, 2009).

Relocation or expansion of agricultural areas and settlements as climate change adaptation measures could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation through bio-energy. Assisted migration (see Section 4.4.2.4) may directly conflict with other conservation priorities, for example by facilitating the introduction of invasive species (Maclachlan et al., 2007).

4.5. Emerging Issues and Key Uncertainties

Detecting the presence and location of thresholds in ecosystem response to climate change, specifically the type of thresholds characterized as tipping points, remains a major source of uncertainty with high potential consequences. In general (Field et al., 2007), negative feedbacks currently dominate the climate-ecosystem interaction. For most ecological processes, increasing magnitude of warming shifts the balance toward positive rather than negative feedbacks (Field et al., 2007). In several regions, such as the boreal ecosystems, positive feedbacks may become dominant, under moderate warming. For positive feedbacks to propagate into "runaway" processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible, and immanent ecological process, but the risk is non-negligible and the consequences if it did occur would be severe; thus further research is needed.

The issue of biophysical interactions between ecosystem state and the climate, over and above the effects mediated through GHGs, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of terrestrial and freshwater ecosystems to climate and other perturbations, particularly at the local scale, remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally complex social systems. The high number of interactions can lead to cascading effects (Biggs et al., 2011). Some of this uncertainty can be reduced by better systems understanding, but some will remain irreducible because of the failure of predictive models when faced with certain types of complexity (such as those which lead to mathematical bifurcations, a problem that is well known in climate science). Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is as yet mostly unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

The consequences for species interactions of differing phenological or movement-based responses to climate change are insufficiently known and may make projections based on individual species models unreliable.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated CO_2 and rising tropospheric ozone on plant productivity—which have critical consequences for the future sink strength of the biosphere, as they are of similar magnitude but opposite sign—are needed as a supplement to the single-factor experiments. For example, uncertainty on the magnitude of CO_2 fertilization is key for forest responses to climate change, particularly in tropical forests, woodlands, and savannas (Cox et al., 2013; Huntingford et al., 2013).

The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones, heat waves, and exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied and, in particular, are seldom adequately represented in ESMs.

Understanding of the rate of climate change that can be tracked or adapted to by organisms is as important as understanding the magnitude of change they can tolerate. Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The capacity for, and limits to, ecological and evolutionary adaptive processes are known only in a few cases. The development and testing of human-assisted adaptation strategies for their cost-effectiveness in reducing risk are prerequisites for their widespread adoption.

The costs of the loss of biodiversity and ecosystem services as a result of climate change are known for only a few cases, or are associated with large uncertainties, as are the costs and benefits of assisting ecosystems and species to adapt to climate change.

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