7 Risk management and decision-making in relation to sustainable development

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Executive summary

Increases in global mean surface temperature are projected to result in continued permafrost degradation and coastal degradation (*high confidence*), increased wildfire, decreased crop yields in low latitudes, decreased food stability, decreased water availability, vegetation loss (*medium confidence*), decreased access to food and increased soil erosion (*low confidence*). There is *high agreement* and *high evidence* that increases in global mean temperature will result in continued increase in global vegetation loss, coastal degradation, as well as decreased crop yields in low latitudes, decreased food stability, decreased access to food and nutrition, and *medium confidence* in continued permafrost degradation and water scarcity in drylands. Impacts are already observed across all components (*high confidence*). Some processes may experience irreversible impacts at lower levels of warming than others. There are high risks from permafrost degradation, and wildfire, coastal degradation, stability of food systems at 1.5°C while high risks from soil erosion, vegetation loss and changes in nutrition only occur at higher temperature thresholds due to increased possibility for adaptation (*medium confidence*). {7.2.2.1, 7.2.2.2, 7.2.2.3; 7.2.2.4; 7.2.2.5; 7.2.2.6; 7.2.2.7; Figure 7.1}

These changes result in compound risks to food systems, human and ecosystem health, livelihoods, the viability of infrastructure, and the value of land (*high confidence*). The experience and dynamics of risk change over time as a result of both human and natural processes (*high confidence*). There is *high confidence* that climate and land changes pose increased risks at certain periods of life (i.e., to the very young and ageing populations) as well as sustained risk to those living in poverty. Response options may also increase risks. For example, domestic efforts to insulate populations from food price spikes associated with climatic stressors in the mid-2000s inadequately prevented food insecurity and poverty, and worsened poverty globally. {7.2.1, 7.2.2, 7.3, Table 7.1}

There is significant regional heterogeneity in risks: tropical regions, including Sub-Saharan Africa, Southeast Asia and Central and South America are particularly vulnerable to decreases in crop yield (*high confidence*). Yield of crops in higher latitudes may initially benefit from warming as well as from higher carbon dioxide (CO_2) concentrations. But temperate zones, including the Mediterranean, North Africa, the Gobi desert, Korea and western United States are susceptible to disruptions from increased drought frequency and intensity, dust storms and fires (*high confidence*). {7.2.2}

Risks related to land degradation, desertification and food security increase with temperature and can reverse development gains in some socio-economic development pathways (*high confidence*). SSP1 reduces the vulnerability and exposure of human and natural systems and thus limits risks resulting from desertification, land degradation and food insecurity compared to SSP3 (*high confidence*). SSP1 is characterised by low population growth, reduced inequalities, land-use regulation, low meat consumption, increased trade and few barriers to adaptation or mitigation. SSP3 has the opposite characteristics. Under SSP1, only a small fraction of the dryland population (around 3% at 3°C for the year 2050) will be exposed and vulnerable to water stress. However under SSP3, around 20% of dryland populations (for the year 2050) will be exposed and vulnerable to water stress by 1.5°C and 24% by 3°C. Similarly under SSP1, at 1.5°C, 2 million people are expected to be exposed and vulnerable to crop yield change. Over 20 million are exposed and vulnerable to crop yield change in SSP3, increasing to 854 million people at 3°C (*low confidence*). Livelihoods deteriorate as a result of these impacts, livelihood migration is accelerated, and strife and conflict is worsened (*medium confidence*). {Cross-Chapter Box 9 in Chapters 6 and 7, 7.2.2, 7.3.2, Table 7.1, Figure 7.2}

Land-based adaptation and mitigation responses pose risks associated with the effectiveness and potential adverse side-effects of measures chosen (*medium confidence*). Adverse side-effects on food security, ecosystem services and water security increase with the scale of bioenergy and bioenergy with carbon capture and storage (BECCS) deployment. In a SSP1 future, bioenergy and BECCS deployment up to 4 million km^2 is compatible with sustainability constraints, whereas risks are already high in a SSP3 future for this scale of deployment. {7.2.3}

There is *high confidence* that policies addressing vicious cycles of poverty, land degradation and greenhouse gas (GHG) emissions implemented in a holistic manner can achieve climate-resilient sustainable development. Choice and implementation of policy instruments determine future climate and land pathways (*medium confidence*). Sustainable development pathways (described in SSP1) supported by effective regulation of land use to reduce environmental trade-offs, reduced reliance on traditional biomass, low growth in consumption and limited meat diets, moderate international trade with connected regional markets, and effective GHG mitigation instruments) can result in lower food prices, fewer people affected by floods and other climatic disruptions, and increases in forested land (*high agreement*, *limited evidence*) (SSP1). A policy pathway with limited regulation of land use, low technology development, resource intensive consumption, constrained trade, and ineffective GHG mitigation instruments can result in food price increases, and significant loss of forest (*high agreement*, *limited evidence*) (SSP3). {3.7.5, 7.2.2, 7.3.4, 7.5.5, 7.5.6, Table 7.1, Cross-Chapter Box 9 in Chapters 6 and 7, Cross-Chapter Box 12 in Chapter 7}

Delaying deep mitigation in other sectors and shifting the burden to the land sector, increases the risk associated with adverse effects on food security and ecosystem services (*high confidence*). The consequences are an increased pressure on land with higher risk of mitigation failure and of temperature overshoot and a transfer of the burden of mitigation and unabated climate change to future generations. Prioritising early decarbonisation with minimal reliance on carbon dioxide removal (CDR) decreases the risk of mitigation failure (*high confidence*). {2.5, 6.2, 6.4, 7.2.1, 7.2.2, 7.2.3, 7.5.6, 7.5.7, Cross-Chapter Box 9 in Chapters 6 and 7}

Trade-offs can occur between using land for climate mitigation or Sustainable Development Goal (SDG) 7 (affordable clean

energy) with biodiversity, food, groundwater and riverine ecosystem services (*medium confidence*). There is *medium confidence* that trade-offs currently do not figure into climate policies and decision making. Small hydro power installations (especially in clusters) can impact downstream river ecological connectivity for fish (*high agreement*, *medium evidence*). Large scale solar farms and wind turbine installations can impact endangered species and disrupt habitat connectivity (*medium agreement*, *medium evidence*). Conversion of rivers for transportation can disrupt fisheries and endangered species (through dredging and traffic) (*medium agreement*, *low evidence*). {7.5.6}

The full mitigation potential assessed in this report will only be realised if agricultural emissions are included in mainstream climate policy (*high agreement*, *high evidence*). Carbon markets are theoretically more cost-effective than taxation but challenging to implement in the land-sector (*high confidence*) Carbon pricing (through carbon markets or carbon taxes) has the potential to be an effective mechanism to reduce GHG emissions, although it remains relatively untested in agriculture and food systems. Equity considerations can be balanced by a mix of both market and non-market mechanisms (*medium evidence*, *medium agreement*). Emissions leakage could be reduced by multi-lateral action (*high agreement*, *medium evidence*). {7.4.6, 7.5.5, 7.5.6, Cross-Chapter Box 9 in Chapters 6 and 7}

A suite of coherent climate and land policies advances the goal of the Paris Agreement and the land-related SDG targets on poverty, hunger, health, sustainable cities and communities, responsible consumption and production, and life on land. There is *high confidence* that acting early will avert or minimise risks, reduce losses and generate returns on investment. The economic costs of action on sustainable land management (SLM), mitigation, and adaptation are less than the consequences of inaction for humans and ecosystems (*medium confidence*). Policy portfolios that make ecological restoration more attractive, people more resilient – expanding financial inclusion, flexible carbon credits, disaster risk and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems – could save 100 billion USD a year, if implemented globally. {7.3.1, 7.4.7, 7.4.8, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

Coordination of policy instruments across scales, levels, and sectors advances co-benefits, manages land and climate risks, advances food security, and addresses equity concerns (*medium confidence*). Flood resilience policies are mutually reinforcing and include flood zone mapping, financial incentives to move, and building restrictions, and insurance. Sustainability certification, technology transfer, land-use standards and secure land tenure schemes, integrated with early action and preparedness, advance response options. SLM improves with investment in agricultural research, environmental farm practices, agri-environmental payments, financial support for sustainable agricultural water infrastructure (including dugouts), agriculture emission trading, and elimination of agricultural subsidies (*medium confidence*). Drought resilience policies (including drought preparedness planning, early warning and monitoring, improving water use efficiency), synergistically improve agricultural producer livelihoods and foster SLM. {3.7.5, Cross-Chapter Box 5 in Chapter 3, 7.4.3, 7.4.6, 7.5.6, 7.4.8, , 7.5.6, 7.6.3}

Technology transfer in land-use sectors offers new opportunities for adaptation, mitigation, international cooperation, R&D collaboration, and local engagement (*medium confidence*). International cooperation to modernise the traditional biomass sector will free up both land and labour for more productive uses. Technology transfer can assist the measurement and accounting of emission reductions by developing countries. {7.4.4, 7.4.6, Cross-Chapter Box 12 in Chapter 7}

Measuring progress towards goals is important in decision-making and adaptive governance to create common understanding and advance policy effectiveness (*high agreement, medium evidence*). Measurable indicators, selected with the participation of people and supporting data collection, are useful for climate policy development and decision-making. Indicators include the SDGs, nationally determined contributions (NDCs), land degradation neutrality (LDN) core indicators, carbon stock measurement, measurement and monitoring for REDD+, metrics for measuring biodiversity and ecosystem services, and governance capacity. {7.5.5, 7.5.7, 7.6.4, 7.6.6}

The complex spatial, cultural and temporal dynamics of risk and uncertainty in relation to land and climate interactions and food security, require a flexible, adaptive, iterative approach to assessing risks, revising decisions and policy instruments (*high confidence*). Adaptive, iterative decision making moves beyond standard economic appraisal techniques to new methods such as dynamic adaptation pathways with risks identified by trigger points through indicators. Scenarios can provide valuable information at all planning stages in relation to land, climate and food; adaptive management addresses uncertainty in scenario planning with pathway choices made and reassessed to respond to new information and data as it becomes available. {3.7.5, 7.4.4, 7.5.2, 7.5.3, 7.5.4, 7.5.7, 7.6.1, 7.6.3}

Indigenous and local knowledge (ILK) can play a key role in understanding climate processes and impacts, adaptation to climate change, sustainable land management (SLM) across different ecosystems, and enhancement of food security (*high confidence*). ILK is context-specific, collective, informally transmitted, and multi-functional, and can encompass factual information about the environment and guidance on management of resources and related rights and social behaviour. ILK can be used in decision-making at various scales and levels, and exchange of experiences with adaptation and mitigation that include ILK is both a requirement and an entry strategy for participatory climate communication and action. Opportunities exist for integration of ILK with scientific knowledge. {7.4.1, 7.4.5, 7.4.6, 7.6.4, Cross-Chapter Box 13 in Chapter 7}

Participation of people in land and climate decision making and policy formation allows for transparent effective solutions and the implementation of response options that advance

synergies, reduce trade-offs in SLM (*medium confidence*), and overcomes barriers to adaptation and mitigation (*high confidence*). Improvements to SLM are achieved by: (i) engaging people in citizen science by mediating and facilitating landscape conservation planning, policy choice, and early warning systems (*medium confidence*); (ii) involving people in identifying problems (including species decline, habitat loss, land-use change in agriculture, food production and forestry), selection of indicators, collection of climate data, land modelling, agricultural innovation opportunities. When social learning is combined with collective action, transformative change can occur addressing tenure issues and changing land-use practices (*medium confidence*). Meaningful participation overcomes barriers by opening up policy and science surrounding climate and land decisions to inclusive discussion that promotes alternatives. {3.7.5, 7.4.1, 7.4.9; 7.5.1, 7.5.4, 7.5.5, 7.5.7, 7.6.4, 7.6.6}

Empowering women can bolster synergies among household food security and SLM (*high confidence*). This can be achieved with policy instruments that account for gender differences. The overwhelming presence of women in many land based activities including agriculture provides opportunities to mainstream gender policies, overcome gender barriers, enhance gender equality, and increase SLM and food security (*high confidence*). Policies that address barriers include gender qualifying criteria and gender appropriate delivery, including access to financing, information, technology, government transfers, training, and extension may be built into existing women's programmes, structures (civil society groups) including collective micro enterprise (*medium confidence*). {Cross-Chapter Box 11 in Chapter 7}

The significant social and political changes required for sustainable land use, reductions in demand and land-based mitigation efforts associated with climate stabilisation require a wide range of governance mechanisms. The expansion and diversification of land use and biomass systems and markets requires hybrid governance: public-private partnerships, transnational, polycentric, and state governance to insure opportunities are maximised, trade-offs are managed equitably and negative impacts are minimised (*medium confidence*). {7.4.6, 7.6.2, 7.6.3, Cross-Chapter Box 7 in Chapter 6}

Land tenure systems have implications for both adaptation and mitigation, which need to be understood within specific socio-economic and legal contexts, and may themselves be impacted by climate change and climate action (*limited evidence*, *high agreement*). Land policy (in a diversity of forms beyond focus on freehold title) can provide routes to land security and facilitate or constrain climate action, across cropping, rangeland, forest, freshwater ecosystems and other systems. Large-scale land acquisitions are an important context for the relations between tenure security and climate change, but their scale, nature and implications are imperfectly understood. There is *medium confidence* that land titling and recognition programmes, particularly those that authorize and respect indigenous and communal tenure, can lead to improved management of forests, including for carbon storage. Strong public coordination (government and public administration) can integrate land policy with national policies on adaptation and reduce sensitivities to climate change. {7.6.2; 7.6.3; 7.6.4, 7.6.5}

Significant gaps in knowledge exist when it comes to understanding the effectiveness of policy instruments and institutions related to land-use management, forestry, agriculture and bioenergy. Interdisciplinary research is needed on the impacts of policies and measures in land sectors. Knowledge gaps are due in part to the highly contextual and local nature of land and climate measures and the long time periods needed to evaluate land-use change in its socio-economic frame, as compared to technological investments in energy or industry that are somewhat more comparable. Significant investment is needed in monitoring, evaluation and assessment of policy impacts across different sectors and levels. {7.7}

7.1 Introduction and relation to other chapters

Land is integral to human habitation and livelihoods, providing food and resources, and also serves as a source of identity and cultural meaning. However, the combined impacts of climate change, desertification, land degradation and food insecurity pose obstacles to resilient development and the achievement of the Sustainable Development Goals (SDGs). This chapter reviews and assesses literature on risk and uncertainty surrounding land and climate change, policy instruments and decision-making that seek to address those risks and uncertainties, and governance practices that advance the response options with co-benefits identified in Chapter 6, lessen the socio-economic impacts of climate change and reduce trade-offs, and advance SLM.

7.1.1 Findings of previous IPCC assessments and reports

This chapter builds on earlier assessments contained in several chapters of the IPCC Fifth Assessment Report (the contributions of both Working Groups II and III), the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC 2012), and the IPCC Special Report on Global Warming of 1.5°C (SR15) (IPCC 2018a). The findings most relevant to decision-making on and governance of responses to land-climate challenges are set out in Box 7.1.

Box 7.1 | Relevant findings of recent IPCC reports

Climate change and sustainable development pathways

"Climate change poses a moderate threat to current sustainable development and a severe threat to future sustainable development" (Denton et al. 2014; Fleurbaey et al. 2014).

Significant transformations may be required for climate-resilient pathways (Denton et al. 2014; Jones et al. 2014).

The design of climate policy is influenced by (i) differing ways that individuals and organisations perceive risks and uncertainties, and (ii) the consideration of a diverse array of risks and uncertainties – as well as human and social responses – which may be difficult to measure, are of low probability but which would have a significant impact if they occurred (Kunreuther et al. 2014; Fleurbaey et al. 2014; Kolstad et al. 2014).

Building climate-resilient pathways requires iterative, continually evolving and complementary processes at all levels of government (Denton et al. 2014; Kunreuther et al. 2014; Kolstad et al. 2014; Somanthan et al. 2014; Lavell et al. 2012).

Important aspects of climate-resilient policies include local level institutions, decentralisation, participatory governance, iterative learning, integration of local knowledge, and reduction of inequality (Dasgupta et al. 2014; Lavell et al. 2012; Cutter et al. 2012b; O'Brien et al. 2012; Roy et al. 2018).

Climate action and sustainable development are linked: adaptation has co-benefits for sustainable development, while "sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming" (IPCC 2018a). Redistributive policies that shield the poor and vulnerable can resolve trade-offs between mitigation objectives and the hunger, poverty and energy access SDGs.

Land and rural livelihoods

Policies and institutions relating to land, including land tenure, can contribute to the vulnerability of rural people, and constrain adaptation. Climate policies, such as encouraging cultivation of biofuels, or payments under REDD+, will have significant secondary impacts, both positive and negative, in some rural areas (Dasgupta et al. 2014).

"Sustainable land management is an effective disaster risk reduction tool" (Cutter et al. 2012a).

Risk and risk management

A variety of emergent risks not previously assessed or recognised, can be identified by taking into account: (i) the "interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions", and (ii) "indirect, trans-boundary, and long-distance impacts of climate change" including price spikes, migration, conflict and the unforeseen impacts of mitigation measures (Oppenheimer et al. 2014).

"Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable" (Oppenheimer et al. 2014).

Decision-making

"Risk management provides a useful framework for most climate change decision-making. Iterative risk management is most suitable in situations characterised by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socio-economic and biophysical changes" (Jones et al. 2014).

"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 organisation and institution" (Jones et al. 2014).

"Scenarios are a key tool for addressing uncertainty", either through problem exploration or solution exploration (Jones et al. 2014).

Box 7.1 (continued)

Governance

There is no single approach to adaptation planning and both top-down and bottom-up approaches are widely recognised. "Institutional dimensions in adaptation governance play a key role in promoting the transition from planning to implementation of adaptation" (Mimura et al. 2014). Adaptation is also essential at all scales, including adaptation by local governments, businesses, communities and individuals (Denton et al. 2014).

"Strengthened multi-level governance, institutional capacity, policy instruments, technological innovation and transfer and mobilisation of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C-consistent systems transitions" (IPCC 2018b).

Governance is key for vulnerability and exposure represented by institutionalised rule systems and habitualised behaviour and norms that govern society and guide actors, and "it is essential to improve knowledge on how to promote adaptive governance within the framework of risk assessment and risk management" (Cardona 2012).

7.1.2 Treatment of key terms in the chapter

While the term **risk** continues to be subject to a growing number of definitions in different disciplines and sectors, this chapter takes as a starting point the definition used in the IPCC Special Report on Global Warming of 1.5°C (SR15) (IPCC 2018a), which reflects definitions used by both Working Group II and Working Group III in the Fifth Assessment Report (AR5): "The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain" (Allwood et al. 2014; Oppenheimer et al. 2014). The SR15 definition further specifies: "In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure." In SR15, as in the IPCC SREX and AR5 WGII, risk is conceptualised as resulting from the interaction of vulnerability (of the affected system), its exposure over time (to a hazard), as well as the (climate-related) impact and the likelihood of its occurrence (AR5 2014; IPCC 2018a, 2012). In the context of SRCCL, risk must also be seen as including risks to the implementation of responses to land–climate challenges from economic, political and governance factors. Climate and land risks must be seen in relation to human values and objectives (Denton et al. 2014). Risk is closely associated with concepts of vulnerability and resilience, which are themselves subject to differing definitions across different knowledge communities.

Risks examined in this chapter arise from more than one of the major land–climate–society challenges (desertification, land degradation, and food insecurity), or partly stem from mitigation or adaptation actions, or cascade across different sectors or geographical locations. They could thus be seen as examples of **emergent risks**: "aris[ing] from the interaction of phenomena in a complex system" (Oppenheimer et al. 2014, p.1052). Stranded assets in the coal sector due to proliferation of renewable energy and government response could be examples of emergent risks (Saluja and Singh 2018; Marcacci 2018). Additionally, the absence of an explicit goal for conserving freshwater ecosystems and ecosystem services in SDGs (in contrast to a goal – 'life below water' – exclusively for marine biodiversity) is related to its trade-offs with energy and irrigation goals, thus posing a substantive risk (Nilsson et al. 2016b; Vörösmarty et al. 2010).

Governance is not previously well defined in IPCC reports, but is used here to include all of the processes, structures, rules and traditions that govern, which may be undertaken by actors including governments, markets, organisations, or families (Bevir 2011), with particular reference to the multitude of actors operating in respect of land–climate interactions. Such definitions of governance allow for it to be decoupled from the more familiar concept of government and studied in the context of complex human–environment relations and environmental and resource regimes (Young 2017a). Governance involves the interactions among formal and informal institutions through which people articulate their interests, exercise their legal rights, meet their legal obligations, and mediate their differences (UNDP 1997).

7.1.3 Roadmap to the chapter

This chapter firstly discusses risks and their drivers, at various scales, in relation to land-climate challenges, including risks associated with responses to climate change (Section 7.2). The consequences of the principal risks in economic and human terms, and associated concepts such as tipping points and windows of opportunity for response are then described (Section 7.3). Policy responses at different scales to different land-climate risks, and barriers to implementation, are described in Section 7.4, followed by an assessment of approaches to decision-making on land-climate challenges (Section 7.5), and questions of the governance of the land-climate interface (Section 7.6). Key uncertainties and knowledge gaps are identified in Section 7.7.

7.2 Climate-related risks for land-based human systems and ecosystems

This section examines risks that climate change poses to selected land-based human systems and ecosystems, and then further explores how social and economic choices, as well as responses to climate change, will exacerbate or lessen risks. 'Risk' is defined as *the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems*. The interacting processes of climate change, land change, and unprecedented social and technological change, pose significant risk to climate-resilient sustainable development. The pace, intensity, and scale of these sizeable risks affect the central issues in sustainable development: access to ecosystem services (ES) and resources essential to sustain people in given locations; how and where people live and work; and the means to safeguard human well-being against disruptions (Warner et al. 2019). In the context of climate change, adverse consequences can arise from the potential *impacts o*f climate change as well as human *responses to* climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ES), ecosystems and species (see Glossary). Risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may change over time and space as a result of socio-economic changes and human decision-making ('risk management'). Numerous uncertainties exist in the scientific understanding of risk (Section 1.2.2).

7.2.1 Assessing risk

This chapter applies and further improves methods used in previous IPCC reports including AR5 and the Special Report on Global Warming of 1.5°C (SR15) to assess risks. Evidence is drawn from published studies, which include observations of impacts from human-induced climate change and model projections for future climate change. Such projections are based on Integrated Assessment Models (IAMs), Earth System Models (ESMs), regional climate models and global or regional impact models examining the impact of climate change on various indicators (Cross-Chapter Box 1 in Chapter 1). Results of laboratory and field experiments that examine impacts of specific changes were also included in the review. Risks under different future socio-economic conditions were assessed using recent publications based on Shared Socio-economic Pathways (SSPs). SSPs provide storylines about future socio-economic development and can be combined with Representative Concentration Pathways RCPs (Riahi et al. 2017) (Cross-Chapter Box 9 in Chapters 6 and 7). Risk arising from land-based mitigation and adaptation choices is assessed using studies examining the adverse side effects of such responses (Section 7.2.3).

Burning embers figures introduced in the IPCC Third Assessment Report through to the Fifth Assessment Report, and the SR15, were developed for this report to illustrate risks at different temperature thresholds. Key components involved in desertification, land degradation and food security were identified, based on discussions with authors in Chapters 3, 4 and 5. The final list of burning embers in Figure 7.1 is not intended to be fully comprehensive, but represents processes for which sufficient literature exists to make expert judgements. Literature used in the burning embers assessment is summarised in tables in Supplementary Material. Following an approach articulated in O'Neill et al. (2017), expert judgements were made to assess thresholds of risk (O'Neill et al. 2017a). To further strengthen replicability of the method, a predefined protocol based on a modified Delphi process was followed (Mukherjee et al. 2015). This included two separate anonymous rating rounds, feedback in between rounds and a group discussion to achieve consensus.

Burning embers provide ranges of a given variable (typically global mean near-surface air temperature) for which risks transitions within four categories: undetectable, moderate, high and very high. **Moderate risk** indicates that impacts are detectable and attributable to climate-related factors. **High risk** indicates widespread impacts on larger numbers or proportion of population/area, but with the potential to adapt or recover. **Very high risk** indicates severe and possibly irreversible impacts with limited ability of societies and ecosystems to adapt to them. Transitions between risk categories were assigned confidence levels based on the amount, and quality, of academic literature supporting judgements: L = low, M = medium, and H = high. Further details of the procedure are provided in Supplementary Material.

7.2.2 Risks to land systems arising from climate change

At current levels of global mean surface temperature (GMST) increase, impacts are already detectable across numerous land-related systems (*high confidence*) (Chapters 2, 3, 4 and 6). There is *high confidence* that unabated future climate change will result in continued changes to processes involved in desertification, land degradation and food security, including: water scarcity in drylands; soil erosion; coastal degradation; vegetation loss; fire; permafrost thaw; and access, stability, utilisation and physical availability of food (Figure 7.1). These changes will increase risks to food systems, the health of humans and ecosystems, livelihoods, the value of land, infrastructure and communities (Section 7.3). Details of the risks, and their transitions, are described in the following subsections.

7.2.2.1 Crop yield in low latitudes

There is *high confidence* that climate change has resulted in decreases in yield (of wheat, rice, maize, soy) and reduced food availability in low-latitude regions (IPCC, 2018) (Section 5.2.2). Countries in low-latitude regions are particularly vulnerable because the livelihoods of high proportions of the population are dependent on agricultural production. Even moderate temperature increases (1°C to 2°C) have negative yield impacts for major cereals, because the climate of many tropical agricultural regions is already quite close to the high-temperature thresholds for suitable production of these cereals (Rosenzweig et al. 2014). Thus, by 1.5°C global mean temperature GMT, or between approximately 1.6°C and approximately 2.6°C of

Risks to humans and ecosystems from changes in land-based processes as a result of climate change

Increases in global mean surface temperature (GMST), relative to pre-industrial levels, affect processes involved in **desertification** (water scarcity), **land degradation** (soil erosion, vegetation loss, wildfire, permafrost thaw) and **food security** (crop yield and food supply instabilities). Changes in these processes drive risks to food systems, livelihoods, infrastructure, the value of land, and human and ecosystem health. Changes in one process (e.g., wildfire or water scarcity) may result in compound risks. Risks are location-specific and differ by region.

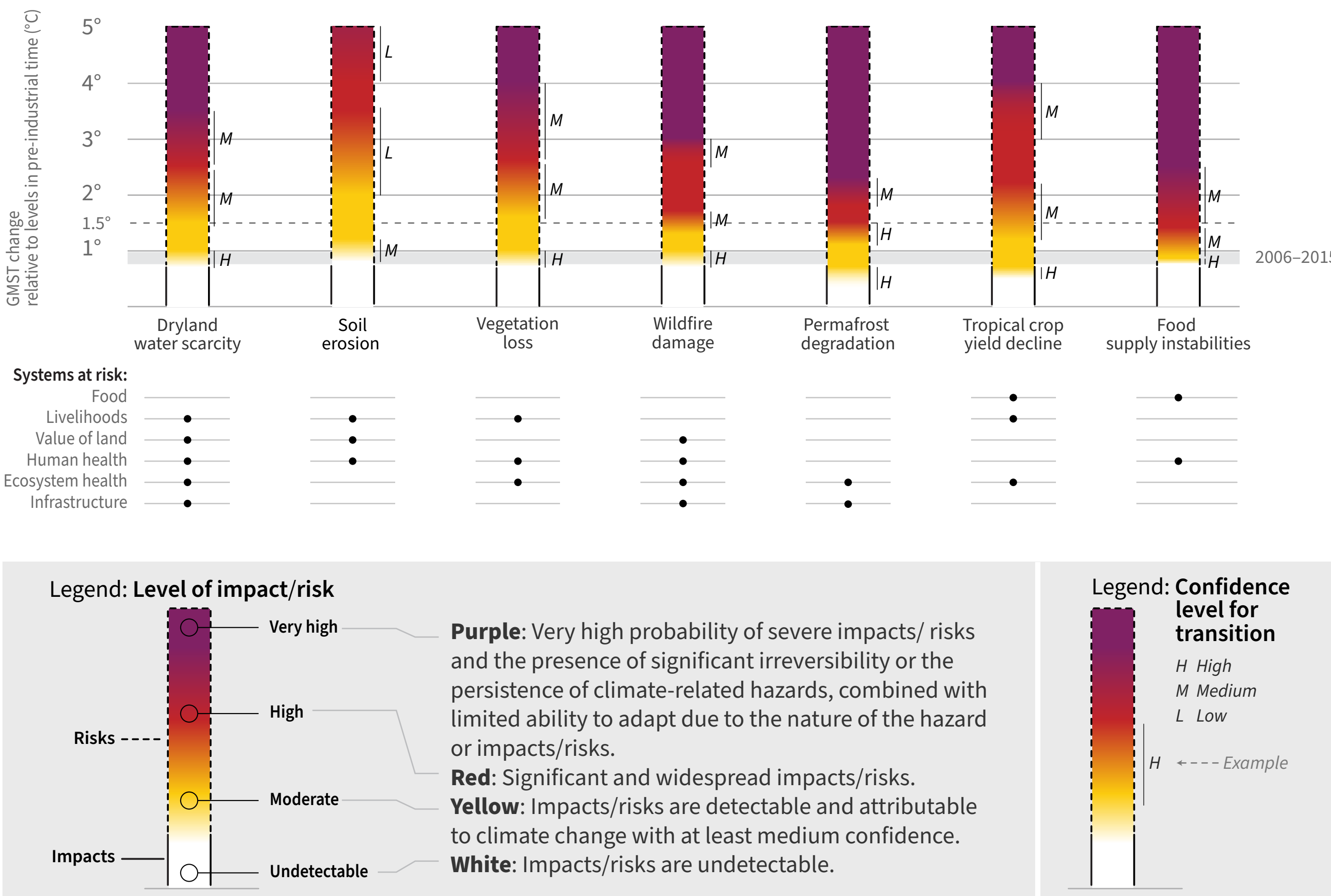

Figure 7.1 | Risks to selected land system elements as a function of global mean surface temperature increase since pre-industrial times. Impacts on human and ecological systems include: 1) economic loss and declines in livelihoods and ecosystem services from water scarcity in drylands, 2) economic loss and declines in livelihoods and ecosystem services from reduced land productivity due to soil erosion, 3) vegetation loss and shifts in vegetation structure, 4) damage to infrastructure, altered land cover, accelerated erosion and increased air pollution from fires, 5) damage to natural and built environment from permafrost thaw related ground instability, 6) changes to crop yield and food availability in low-latitude regions and 7) increased disruption of food supply stability. Risks are global (2, 3, 4, 7) and specific to certain regions (1, 5, 6). Selected components are illustrative and not intended to be fully comprehensive of factors influencing food security, land degradation and desertification. The supporting literature and methods are provided in Supplementary Material. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway.

local warming, risks to yields may already transition to *high* in West Africa, Southeast Asia and Central and South America (Faye et al. 2018) (*medium confidence*). For further information see Section 5.3.2.1. By contrast, higher latitudes may initially benefit from warming as well as well higher CO_2 concentrations (IPCC 2018a). Wheat yield losses are expected to be lower for the USA (–5.5 ± 4.4% per degree Celsius) and France (–6.0 ± 4.2% per degree Celsius) compared to India (–9.1 ± 5.4% per degree Celsius) (Zhao et al. 2017). Very high risks to low-latitude yields may occur between 3°C and 4°C (*medium confidence*). At these temperatures, catastrophic reductions in crop yields may occur, of up to 60% in low latitudes (Rosenzweig et al. 2014) (Sections 5.2.2 and 5.2.3). Some studies report significant population displacement from the tropics related to systemic livelihood disruption in agriculture systems (Tittonell 2014; Montaña et al. 2016; Huber-Sannwald et al. 2012; Wise et al. 2016; Tanner et al. 2015; Mohapatra 2013). However, at higher temperatures of warming, all regions of the world face risks of declining yields as a result of extreme weather events and reduced heat tolerance of maize, rice, wheat and soy (Zhao et al. 2017; IPCC 2018a).

7.2.2.2 Food supply instability

Stability of food supply is expected to decrease as the magnitude and frequency of extreme events increase, disrupting food chains in all areas of the world (*medium evidence*, *high agreement*) (Wheeler and Von Braun 2013; Coates 2013; Puma et al. 2015; Deryng et al. 2014; Harvey et al. 2014b; Iizumi et al. 2013; Seaman et al. 2014) (Sections 5.3.2, 5.3.3, 5.6.2 and 5.7.1). While international trade in food is assumed to be a key response for alleviating hunger, historical data and economic models suggest that international trade does not adequately redistribute food globally to offset yield declines or other food shortages when weather extremes reduce crop yields (*medium confidence*) (Schmitz et al. 2012; Chatzopoulos et al. 2019; Marchand et al. 2016; Gilbert 2010; Wellesley et al. 2017). When droughts, heat waves, floods or other extremes destroy crops, evidence has shown that exports are constrained in key producing countries contributing to price spikes and social tension in importing countries which reduce access to food (*medium evidence*, *medium agreement*) (von Uexkull et al. 2016; Gleick 2014; Maystadt and Ecker 2014; Kelley et al. 2015; Church et al. 2017; Götz et al. 2013; Puma et al. 2015; Willenbockel 2012; Headey 2011; Distefano et al. 2018; Brooks 2014). There is little understanding of how food system shocks cascade through a modern interconnected economy. Reliance on global markets may reduce some risks, but the ongoing globalisation of food trade networks exposes the world food system to new impacts that have not been seen in the past (Sections 5.1.2, 5.2.1, 5.5.2.5, 5.6.5 and 5.7.1). The global food system is vulnerable to systemic disruptions and increasingly interconnected inter-country food dependencies, and changes in the frequency and severity of extreme weather events may complicate future responses (Puma et al. 2015; Jones and Hiller 2017).

Impacts of climate change are already detectable on food supply and access as price and trade reactions have occurred in response to heatwaves, droughts and other extreme events (*high evidence*, *high agreement*) (Noble et al. 2014; O'Neill et al. 2017b). The impact of climate change on food stability is underexplored (Schleussner et al. 2016; James et al. 2017). However, some literature assesses that by about 2035, daily maximum temperatures will exceed the 90th percentile of historical (1961–1990) temperatures on 25–30% of days (O'Neill et al. 2017b, Figures 11–17) with negative shocks to food stability and world food prices. O'Neill et al. (2017b) remark that in the future, return periods for precipitation events globally (land only) will reduce from one-in-20-year (historical) to about one-in-14-year or less by 2046–2065 in many areas of the world. Domestic efforts to insulate populations from food price spikes associated with climatic stressors in the mid-2000s have been shown to inadequately shield from poverty, and worsen poverty globally (Diffenbaugh et al. 2012; Meyfroidt et al. 2013; Hertel et al. 2010). The transition to *high risk* is estimated to occur around 1.4°C, possibly by 2035, due to changes in temperature and heavy precipitation events (*medium confidence*) (O'Neill et al. 2017b; Fritsche et al. 2017a; Harvey et al. 2014b). *Very high risk* may occur by 2.4°C (*medium confidence*) and 4°C of warming is considered catastrophic (IPCC 2018c; Noble et al. 2014) for food stability and access because a combination of extreme events, compounding political and social factors, and shocks to crop yields can heavily constrain options to ensure food security in import-reliant countries.

7.2.2.3 Soil erosion

Soil erosion increases risks of economic loss and declines in livelihoods due to reduced land productivity. In the EU, on-site costs of soil erosion by wind has been reported at an average of 55 USD per hectare annually, but up to 450 USD per hectare for sugar beet and oilseed rape (Middleton et al. 2017). Farmers in the Dapo watershed in Ethiopia lose about 220 USD per hectare of maize due to loss of nitrogen through soil erosion (Erkossa et al. 2015). Soil erosion not only increases crop loss but has been shown to have reduced household food supply with older farmers most vulnerable to losses from erosion (Ighodaro et al. 2016). Erosion also results in increased risks to human health, through air pollution from aerosols (Middleton et al. 2017), and brings risks of reduced ES including supporting services related to soil formation.

At current levels of warming, changes in erosion are already detected in many regions. Attribution to climate change is challenging as there are other powerful drivers of erosion (e.g., land use), limited global-scale studies (Li and Fang 2016a; Vanmaercke et al. 2016a) and the absence of formal detection and attribution studies (Section 4.2.3). However, studies have found an increase in short-duration and high-intensity precipitation, due to anthropogenic climate change, which is a causative factor for soil erosion (Lenderink and van Meijgaard 2008; Li and Fang 2016b). High risks of erosion may occur between 2°C and 3.5°C (*low confidence*) as continued increases in intense precipitation are projected at these temperature thresholds (Fischer and Knutti 2015) in many regions. Warming also reduces soil organic matter, diminishing resistance against erosion. There is *low confidence* concerning the temperature threshold at which risks become *very high* due to large regional differences and limited global-scale studies (Li and Fang 2016b; Vanmaercke et al. 2016b) (Section 4.4).

7.2.2.4 Dryland water scarcity

Water scarcity in drylands contributes to changes in desertification and hazards such as dust storms, increasing risks of economic loss, declines in livelihoods of communities and negative health effects (*high confidence*) (Section 3.1.3). Further information specific to costs and impacts of water scarcity and droughts is detailed in Cross-Chapter Box 5 in Chapter 3.

The IPCC AR5 report and the SR15 concluded that there is *low confidence* in the direction of drought trends since 1950 at the global scale. While these reports did not assess water scarcity with a specific focus on drylands, they indicated that there is *high confidence* in observed drought increases in some regions of the world, including in the Mediterranean and West Africa (IPCC AR5) and that there is *medium confidence* that anthropogenic climate change has contributed to increased drying in the Mediterranean region (including southern Europe, northern Africa and the western Asia and the Middle east) and that this tendency will continue to increase under higher levels of global warming (IPCC 2018d). Some parts of the drylands have experienced decreasing precipitation over recent decades (IPCC AR5) (Chapter 3 and Section 3.2), consistent with the fact that climate change is implicated in desertification trends in some regions (Section 3.2.2). Dust storms, linked to changes in precipitation and vegetation, appear to be occurring with greater frequency in some deserts and their margins (Goudie 2014) (Section 3.3.1). There is therefore *high confidence* that the transition from *undetectable* to *moderate risk* associated with water scarcity in drylands occurred in recent decades in the range 0.7°C to 1°C (Figure 7.1).

Between 1.5°C and 2.5°C, the risk level is expected to increase from *moderate* to *high* (*medium confidence*). Globally, at 2°C an additional 8% of the world population (of population in 2000) will be exposed to new forms of or aggravated water scarcity (IPCC 2018d). However, at 2°C, the annual warming over drylands will reach 3.2°C–4.0°C, implying about 44% more warming over drylands than humid lands (Huang et al. 2017), thus potentially aggravating water scarcity issues through increased evaporative demand. Byers et al. (2018a) estimate that 3–22% of the drylands population (range depending on socio-economic conditions) will be exposed and vulnerable to water stress. The Mediterranean, North Africa and the Eastern Mediterranean will be particularly vulnerable to water shortages, and expansion of desert terrain and vegetation is predicted to occur in the Mediterranean biome, an unparalleled change in the last 10,000 years (*medium confidence*) (IPCC 2018d). At 2.5°C–3.5°C risks are expected to become *very high* with migration from some drylands resulting as the only adaptation option (*medium confidence*). Scarcity of water for irrigation is expected to increase, in particular in Mediterranean regions, with limited possibilities for adaptation (Haddeland et al. 2014).

7.2.2.5 Vegetation degradation

There are clear links between climate change and vegetation cover changes, tree mortality, forest diseases, insect outbreaks, forest fires, forest productivity and net ecosystem biome production (Allen et al. 2010; Bentz et al. 2010; Anderegg et al. 2013; Hember et al. 2017; Song et al. 2018; Sturrock et al. 2011). Forest dieback, often a result of drought and temperature changes, not only produces risks to forest ecosystems but also to people with livelihoods dependent on forests. A 50-year study of temperate forest, dominated by beech (*Fagus sylvatica* L.), documented a 33% decline in basal area and a 70% decline in juvenile tree species, possibly as a result of interacting pressures of drought, overgrazing and pathogens (Martin et al. 2015). There is *high confidence* that such dieback impacts ecosystem properties and services including soil microbial community structure (Gazol et al. 2018). Forest managers and users have reported negative emotional impacts from forest dieback such as pessimism about losses, hopelessness and fear (Oakes et al. 2016). Practices and policies such as forest classification systems, projection of growth, yield and models for timber supply are already being affected by climate change (Sturrock et al. 2011).

While risks to ecosystems and livelihoods from vegetation degradation are already detectable at current levels of GMT increase, risks are expected to reach *high* levels between 1.6°C and 2.6°C (*medium confidence*). Significant uncertainty exists due to countervailing factors: CO_2 fertilisation encourages forest expansion but increased drought, insect outbreaks, and fires result in dieback (Bonan 2008; Lindner et al. 2010). The combined effects of temperature and precipitation change, with CO_2 fertilisation, make future risks to forests very location specific. It is challenging therefore to make global estimates. However, even locally specific studies make clear that *very high risks* occur between 2.6°C and 4°C (*medium confidence*). Australian tropical rainforests experience significant loss of biodiversity with 3.5°C increase. At this level of increase there are no areas with greater than 30 species, and all endemics disappear from low- and mid-elevation regions (Williams et al. 2003). Mountain ecosystems are particularly vulnerable (Loarie et al. 2009).

7.2.2.6 Fire damage

Increasing fires result in heightened risks to infrastructure, accelerated erosion, altered hydrology, increased air pollution, and negative mental health impacts. Fire not only destroys property but induces changes in underlying site conditions (ground cover, soil water repellency, aggregate stability and surface roughness) which amplifies runoff and erosion, increasing future risks to property and human lives during extreme rainfall events (Pierson and Williams 2016). Dust and ash from fires can impact air quality in a wide area. For example, a dust plume from a fire in Idaho, USA, in September 2010 was visible in MODIS satellite imagery and extended at least 100 km downwind of the source area (Wagenbrenner et al. 2013). Individuals can suffer from property damage or direct injury, psychological trauma, depression, and post traumatic stress disorder, and have reported negative impacts to well-being from loss of connection to landscape (Paveglio et al. 2016; Sharples et al. 2016a). Costs of large wildfires in the USA can exceed 20 million USD per day (Pierson et al. 2011) and has been estimated at 8.5 billion USD per year in Australia (Sharples et al. 2016b). Globally, human exposure to fire will increase due to projected population growth in fire-prone regions (Knorr et al. 2016a).

It is not clear how quickly, or even if, systems can recover from fires. Longevity of effects may differ depending on cover recruitment rate and soil conditions, recovering in one to two seasons or over 10 growing seasons (Pierson et al. 2011). In Russia, one-third of forest area affected by fires turned into unproductive areas where natural reforestation is not possible within 2–3 lifecycles of major forest forming species (i.e., 300–600 years) (Shvidenko et al. 2012).

Risks under current warming levels are already *moderate* as anthropogenic climate change has caused significant increases in fire area (*high confidence*) due to availability of detection and attribution studies) (Cross-Chapter Box 3 in Chapter 2). This has been detected and attributed regionally, notably in the western USA (Abatzoglou and Williams 2016; Westerling et al. 2006; Dennison et al. 2014), Indonesia (Fernandes et al. 2017) and other regions (Jolly et al. 2015). Regional increases have been observed despite a global-average declining trend induced by human fire-suppression strategies, especially in savannahs (Yang et al. 2014a; Andela et al. 2017).

High risks of fire may occur between 1.3°C and 1.7°C (*medium confidence*). Studies note heightened risks above 1.5°C as fire, weather, and land prone to fire increase (Abatzoglou et al. 2019a), with *medium confidence* in this transition, due to complex interplay between (i) global warming, (ii) CO_2-fertilisation, and (iii) human/economic factors affecting fire risk. Canada, the USA and the Mediterranean may be particularly vulnerable as the combination of increased fuel due to CO_2 fertilisation, and weather conditions conducive to fire increase risks to people and property. Some studies show substantial effects at 3°C (Knorr et al. 2016b; Abatzoglou et al. 2019b), indicating a transition to *very high risks* (*medium confidence*). At high warming levels, climate change may become the primary driver of fire risk in the extratropics (Knorr et al. 2016b; Abatzoglou et al. 2019b; Yang et al. 2014b). Pyroconvection activity may increase, in areas such as southeast Australia (Dowdy and Pepler 2018), posing major challenges to adaptation.

7.2.2.7 Permafrost

There is a risk of damage to the natural and built environment from permafrost thaw-related ground instability. Residential, transportation, and industrial infrastructure in the pan-Arctic permafrost area are particularly at risk (Hjort et al. 2018). *High risks* already exist at low temperatures (*high confidence*). Approximately, 21–37% of Arctic permafrost is projected to thaw under a 1.5°C of warming (Hoegh-Guldberg et al. 2018). This increases to *very high risk* around 2°C (between 1.8°C and 2.3°C) of temperature increase since pre-industrial times (*medium confidence*) with 35–47% of the Arctic permafrost thawing (Hoegh-Guldberg et al. 2018). If climate stabilised at 2°C, still approximately 40% of permafrost area would be lost (Chadburn et al. 2017), leading to nearly four million people and 70% of current infrastructure in the pan-Arctic permafrost area exposed to permafrost thaw and high hazard (Hjort et al. 2018). Indeed between 2°C and 3°C a collapse of permafrost may occur with a drastic biome shift from tundra to boreal forest (Drijfhout et al. 2015; SR15). There is mixed evidence of a tipping point in permafrost collapse, leading to enhanced greenhouse gas (GHG) emission – particularly methane – between 2°C and 3°C (Hoegh-Guldberg et al. 2018).

7.2.2.8 Risks of desertification, land degradation and food insecurity under different Future Development Pathways

Socio-economic developments and policy choices that govern land–climate interactions are an important driver of risk, along with climate change (*very high confidence*). Risks under two different Shared Socio-economic Pathways (SSPs) were assessed using emerging literature. SSP1 is characterised by low population growth, reduced inequalities, land-use regulation, low meat consumption, and moderate trade (Riahi et al. 2017; Popp et al. 2017a). SSP3 is characterised by high population growth, higher inequalities, limited land-use regulation, resource-intensive consumption including meat-intensive diets, and constrained trade (for further details see Chapter 1 and Cross-Chapter Box 9 in Chapters 6 and 7). These two SSPs, among the set of five SSPs, were selected because they illustrate contrasting futures, ranging from low (SSP1) to high (SSP3) challenges to mitigation and adaptation. Figure 7.2 shows that for a given global mean temperature (GMT) change, risks are different under SSP1 compared to SSP3. In SSP1, global temperature change does not increase above 3°C even in the baseline case (i.e., with no additional mitigation measures) because in this pathway the combination of low population and autonomous improvements, for example, in terms of carbon intensity and/or energy intensity, effectively act as mitigation measures (Riahi et al. 2017). Thus Figure 7.2 does not indicate risks beyond this point in either SSP1 and SSP3. Literature based on such socio-economic and climate models is still emerging and there is a need for greater research on impacts of different pathways. There are few SSP studies exploring aspects of desertification and land degradation, but a greater number of SSP studies on food security (Supplementary Material). SSP1 reduces the vulnerability and exposure of human and natural systems and thus limits risks resulting from desertification, land degradation and food insecurity compared to SSP3 (*high confidence*).

Changes to the water cycle due to global warming are an essential driver of desertification and of the risks to livelihood, food production and vegetation in dryland regions. Changes in water scarcity due to climate change have already been detected in some dryland regions (Section 7.2.2.4) and therefore the transition to *moderate risk* occurred in recent decades (*high confidence*). IPCC (2018d) noted that in the case of risks to water resources, socio-economic drivers are expected to have a greater influence than the changes in climate (*medium confidence*). Indeed, in SSP1 there is only moderate risk even at 3°C of warming, due to the lower exposure and vulnerability of human population (Hanasaki et al. 2013a; Arnell and Lloyd-Hughes 2014; Byers et al. 2018b). Considering drylands only, Byers et al. (2018b) estimate, using a time-sampling approach for climate change and the 2050 population, that at 1.5°C, 2°C and 3°C, the dryland population exposed and vulnerable to water stress in SSP1 will be 2%, 3% and 3% respectively, thus indicating relatively stable *moderate risks*. In SSP3, the transition from *moderate* to *high risk* occurs in the range 1.2°C to 1.5°C (*medium confidence*) and the transition from *high* to *very high risk* is in the range 1.5°C to 2.8°C (*medium confidence*). Hanasaki et al. (2013b) found a consistent increase in water stress at higher warming levels due in large part to growth in population and demand for energy and agricultural commodities, and to a lesser extent due to hydrological changes induced by global warming. In SSP3, Byers et al. (2018b) estimate that at 1.5°C, 2°C and 3°C, the population exposed and vulnerable to water stress in drylands will steadily increase from 20% to 22% and 24% respectively, thus indicating overall much higher risks compared to SSP1 for the same global warming levels.

SSP studies relevant to land degradation assess risks such as: number of people exposed to fire; the costs of floods and coastal flooding; and loss of ES including the ability of land to sequester carbon. The risks related to permafrost melting (Section 7.2.2.7) are not considered here due to the lack of SSP studies addressing this topic. Climate change impacts on various components of land degradation have already been detected (Sections 7.2.2.3, 7.2.2.5 and 7.2.2.6) and therefore the transition from *undetectable* to *moderate risk* is in the range 0.7°C to 1°C (*high confidence*). Less than 100 million people are exposed to habitat degradation at 1.5°C under SSP1 in non-dryland regions, increasing to 257 million at 2°C (Byers

Different socioeconomic pathways affect levels of climate related risks

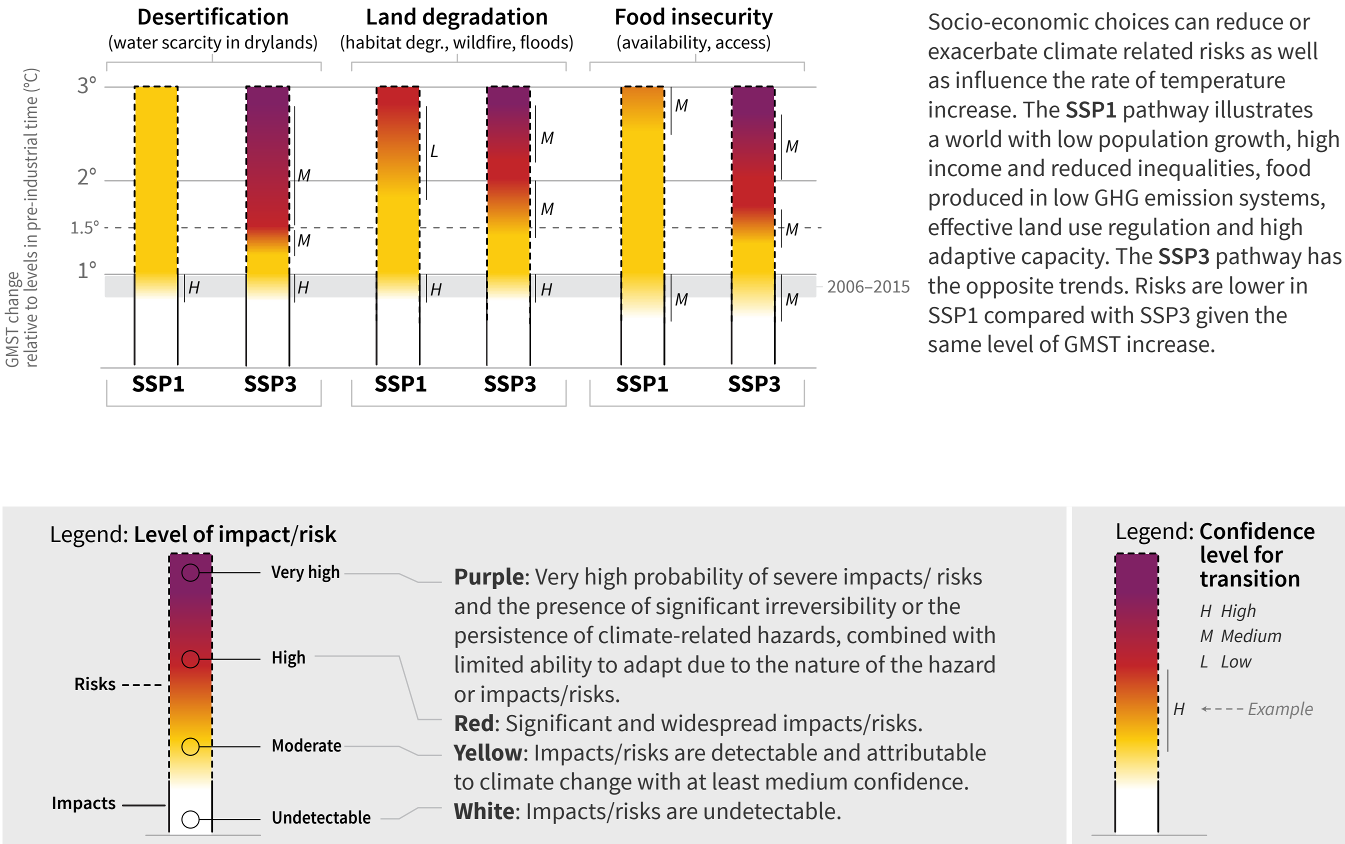

Figure 7.2 | Risks associated with desertification, land degradation and food security due to climate change and patterns of socio-economic development. Increasing risks associated with desertification include population exposed and vulnerable to water scarcity in drylands. Risks related to land degradation include increased habitat degradation, population exposed to wildfire and floods and costs of floods. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable due to childhood underweight. The risks are assessed for two contrasted socio-economic futures (SSP1 and SSP3) under unmitigated climate change {3.6, 4.3.1.2, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 6.2.4, 7.3}. Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change.

et al. 2018). This suggests a gradual transition to *high risk* in the range 1.8°C to 2.8°C, but a *low confidence* is attributed due to the very limited evidence to constrain this transition.

By contrast in SSP3, there are already 107 million people exposed to habitat degradation at 1.5°C, increasing to 1156 million people at 3°C (Byers et al. 2018b). Furthermore, Knorr et al. (2016b) estimate that 646 million people will be exposed to fire at 2°C warming, the main risk driver being the high population growth in SSP3 rather than increased burned area due to climate change. Exposure to extreme rainfall, a causative factor for soil erosion and flooding, also differs under SSPs. Under SSP1 up to 14% of the land and population experience five-day extreme precipitation events. Similar levels of exposure occur at lower temperatures in SSP3 (Zhang et al. 2018b). Population exposed to coastal flooding is lowest under SSP1 and higher under SSP3 with a limited effect of enhanced protection in SSP3 already after 2°C warming (Hinkel et al. 2014). The transition from *high* to *very high risk* will occur at 2.2°Cto 2.8°C in SSP3 (*medium confidence*), whereas this level of risk is not expected to be reached in SSP1.

The greatest number of SSP studies explore climate change impacts relevant to food security, including population at risk of hunger, food price increases, increases in disability adjusted life years (Hasegawa et al. 2018a; Wiebe et al. 2015a; van Meijl et al. 2018a; Byers et al. 2018b). Changes in crop yields and food supply stability have already been attributed to climate change (Sections 7.2.2.1 and 7.2.2.2) and the transition from *undetectable* to *moderate risk* is placed at 0.5°C to 1°C (*medium confidence*). At 1.5°C, about two million people are exposed and vulnerable to crop yield change in SSP1 (Hasegawa et al. 2018b; Byers et al. 2018b), implying *moderate risk*. A transition from *moderate* to *high risk* is expected above 2.5°C (*medium confidence*) with population at risk of hunger of the order of 100 million (Byers et al. 2018b). Under SSP3, *high risks* already exist at 1.5°C (*medium confidence*), with 20 million people exposed and vulnerable to crop yield change. By 2°C, 178 million are vulnerable and 854 million people are vulnerable at 3°C (Byers et al. 2018b). This is supported by the higher food prices increase of up to 20% in 2050 in an RCP6.0 scenario (i.e., slightly below 2°C) in SSP3 compared to up to 5% in SSP1 (van Meijl et al. 2018). Furthermore in SSP3, restricted trade increase this price effect (Wiebe et al. 2015). In SSP3, the transition from *high* to *very high risk* is in the range 2°C to 2.7°C (*medium confidence*) while this transition is never reached in SSP1. This overall confirms that socio-economic development, by affecting exposure and vulnerability, has an even larger effect than climate change for future trends in the population at risk of hunger (O'Neill et al. 2017, p.32). Changes can also threaten development gains (*medium confidence*). Disability adjusted life years due to childhood underweight decline in both SSP1 and SSP3 by 2030 (by 36.4 million disability adjusted life years in SSP1 and 16.2 million in SSP3). However by 2050, disability adjusted life years increase by 43.7 million in SSP3 (Ishida et al. 2014).

7.2.3 Risks arising from responses to climate change

7.2.3.1 Risk associated with land-based adaptation

Land-based adaptation relates to a particular category of adaptation measures relying on land management (Sanz et al. 2017). While most land-based adaptation options provide co-benefits for climate mitigation and other land challenges (Chapter 6 and Section 6.4.1), in some contexts adaptation measures can have adverse side effects, thus implying a risk to socio-ecological systems.

One example of risk is the possible decrease in farmer income when applying adaptive cropland management measures. For instance, conservation agriculture including the principle of no-till farming, contributes to soil erosion management (Chapter 6 and Section 6.2). Yet, no-till management can reduce crop yields in some regions, and although this effect is minimised when no-till farming is complemented by the other two principles of conservation agriculture (residue retention and crop rotation), this could induce a risk to livelihood in vulnerable smallholder farming systems (Pittelkow et al. 2015).

Another example is the use of irrigation against water scarcity and drought. During the long lasting drought from 2007–2009 in California, USA, farmers adapted by relying on groundwater withdrawal and caused groundwater depletion at unsustainable levels (Christian-Smith et al. 2015). The long-term effects of irrigation from groundwater may cause groundwater depletion, land subsidence, aquifer overdraft, and saltwater intrusion (Tularam and Krishna 2009). Therefore, it is expected to increase the vulnerability of coastal aquifers to climate change due to groundwater usage (Ferguson and Gleeson 2012). The long-term practice of irrigation from groundwater may cause a severe combination of potential side effects and consequently irreversible results.

7.2.3.2 Risk associated with land-based mitigation

While historically land-use activities have been a net source of GHG emissions, in future decades the land sector will not only need to reduce its emissions, but also to deliver negative emissions through carbon dioxide removal (CDR) to reach the objective of limiting global warming to 2°C or below (Section 2.5). Although land-based mitigation in itself is a risk-reduction strategy aiming at abating climate change, it also entails risks to humans and ecosystems, depending on the type of measures and the scale of deployment. These risks fall broadly into two categories: risk of mitigation failure – due to uncertainties about mitigation potential, potential for sink reversal and moral hazard; and risks arising from adverse side effects – due to increased competition for land and water resources. This section focuses specifically on bioenergy and bioenergy with carbon capture and storage (BECCS) since it is one of the most prominent land-based mitigation strategies in future mitigation scenarios (along with large-scale forest expansion, which is discussed in Cross-Chapter Box 1 in Chapter 1). Bioenergy and BECCS is assessed in Chapter 6 as being, at large scales, the only response option with adverse side effects across all dimensions (adaptation, food security, land degradation and desertification) (Section 6.4.1).

Risk of mitigation failure. The mitigation potential from bioenergy and BECCS is highly uncertain, with estimates ranging from 0.4 to 11.3 $GtCO_2e\ yr^{-1}$ for the technical potential, while consideration of sustainability constraints suggest an upper end around 5 $GtCO_2e\ yr^{-1}$ (Chapter 2, Section 2.6). In comparison, IAM-based mitigation pathways compatible with limiting global warming at 1.5°C project bioenergy and BECCS deployment exceeding this range (Figure 2.24 in Chapter 2). There is *medium confidence* that IAMs currently do not reflect the lower end and exceed the upper end of bioenergy and BECCS mitigation potential estimates (Anderson and Peters 2016; Krause et al. 2018; IPCC 2018c), with implications for the risk associated with reliance on bioenergy and BECCS deployment for climate mitigation.

In addition, land-based CDR strategies are subject to a risk of carbon sink reversal. This implies a fundamental asymmetry between mitigation achieved through fossil fuel emissions reduction compared to CDR. While carbon in fossil fuel reserves – in the case of avoided fossil fuel emissions – is locked permanently (at least over a time scale of several thousand years), carbon sequestered into the terrestrial biosphere – to compensate fossil fuel emissions – is subject to various disturbances, in particular from climate change and associated extreme events (Fuss et al. 2018; Dooley and Kartha 2018). The probability of sink reversal therefore increases with climate change, implying that the effectiveness of land-based mitigation depends on emission reductions in other sectors and can be sensitive to temperature overshoot (*high confidence*). In the case of bioenergy associated with CCS (BECCS), the issue of the long-term stability of the carbon storage is linked to technical and geological constraints, independent of climate change but presenting risks due to limited knowledge and experience (Chapter 6 and Cross-Chapter Box 7 in Chapter 6).

Another factor in the risk of mitigation failure, is the moral hazard associated with CDR technologies. There is *medium evidence* and *medium agreement* that the promise of future CDR deployment – bioenergy and BECCS in particular – can deter or delay ambitious emission reductions in other sectors (Anderson and Peters 2016; Markusson et al. 2018a; Shue 2018a). The consequences are an increased pressure on land with higher risk of mitigation failure and of temperature overshoot, and a transfer of the burden of mitigation and unabated climate change to future generations. Overall, there is therefore *medium evidence* and *high agreement* that prioritising early decarbonisation with minimal reliance on CDR decreases the risk of mitigation failure and increases intergenerational equity (Geden et al. 2019; Larkin et al. 2018; Markusson et al. 2018b; Shue 2018b).

Risk from adverse side-effects. At large scales, bioenergy (with or without CCS) is expected to increase competition for land, water resources and nutrients, thus exacerbating the risks of food insecurity, loss of ES and water scarcity (Chapter 6 and Cross-Chapter Box 7 in Chapter 6). Figure 7.3 shows the risk level (from *undetectable* to *very high*, aggregating risks of food insecurity, loss of ES and water scarcity) as a function of the global amount of land (million km^2) used for bioenergy, considering second generation bioenergy. Two illustrative future Socio-economic Pathways (SSP1 and SSP3; see Section 7.2.2 for more details) are depicted: in SSP3 the competition for land is exacerbated compared to SSP1 due to higher food demand resulting from larger population growth and higher consumption of meat-based products. The literature used in this assessment is based on IAM and non-IAM-based studies examining the impact of bioenergy crop deployment on various indicators, including food security (food prices or population at risk of hunger with explicit consideration of exposure and vulnerability), SDGs, ecosystem losses, transgression of various planetary boundaries and water consumption (see Supplementary Material). Since most of the assessed literature is centred around 2050, prevailing demographic and economic conditions for this year are used for the risk estimate. An aggregated risk metric including risks of food insecurity, loss of ES and water scarcity is used because there is no unique relationship between bioenergy deployment and the risk outcome for a single system. For instance, bioenergy deployment can be implemented in such a way that food security is prioritised at the expense of natural ecosystems, while the same scale of bioenergy deployment implemented with ecosystem safeguards would lead to a fundamentally different outcome in terms of food security (Boysen et al. 2017a). Considered as a combined risk, however, the possibility of a negative outcome on either food security, ecosystems or both can be assessed with less ambiguity and independently of possible implementation choices.

In SSP1, there is *medium confidence* that 1 to 4 million km^2 can be dedicated to bioenergy production without significant risks to food security, ES and water scarcity. At these scales of deployment, bioenergy and BECCS could have co-benefits for instance by contributing to restoration of degraded land and soils (Cross-Chapter Box 7 in Chapter 6). Although currently degraded soils (up to 20 million km^2) represent a large amount of potentially available land (Boysen et al. 2017a), trade-offs would occur already at smaller scale due to fertiliser and water use (Hejazi et al. 2014; Humpenöder et al. 2017; Heck et al. 2018a; Boysen et al. 2017b). There is *low confidence* that the transition from moderate to high risk is in the range 6–8.7 million km^2. In SSP1, (Humpenöder et al. 2017) found no important impacts on sustainability indicators at a level of 6.7 million km^2, while (Heck et al. 2018b) note that several planetary boundaries (biosphere integrity; land-system change; biogeochemical flows; freshwater use) would be exceeded above 8.7 million km^2.

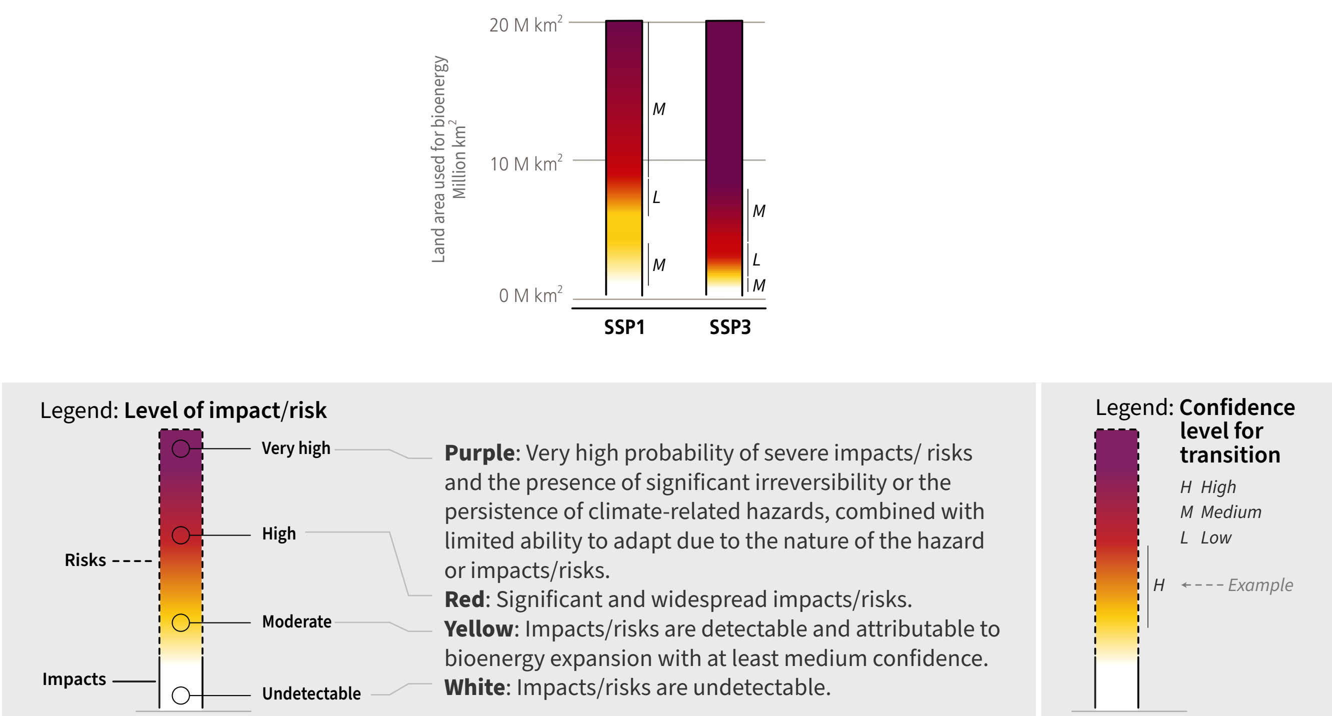

Figure 7.3 | Risks associated with bioenergy crop deployment as a land-based mitigation strategy under two SSPs (SSP1 and SSP3). The assessement is based on literature investigating the consequences of bioenergy expansion for food security, ecosystem loss and water scarcity. These risk indicators were aggregated as a single risk metric in the figure. In this context, very high risk indicates that important adverse consequences are expected for all these indicators (more than 100 million people at risk of hunger, major ecosystem losses and severe water scarcity issues). The climate scenario considered is a mitigation scenario consistent with limiting global warming at 2°C (RCP2.6), however some studies considering other scenarios (e.g., no climate change) were considered in the expert judgement as well as results from other SSPs (e.g., SSP2). The literature supporting the assessment is provided in Table SM7.3.

There is *very high confidence* that all the risk transitions occur at lower bioenergy levels in SSP3, implying higher risks associated with bioenergy deployment, due to the higher competition for land in this pathway. In SSP3, land-based mitigation is therefore strongly limited by sustainability constraints such that moderate risk occur already between 0.5 and 1.5 million km^2 (*medium confidence*). There is *medium confidence* that a bioenergy footprint beyond 4 to 8 million km^2 would entail very high risk with transgression of most planetary boundaries (Heck et al. 2018b), strong decline in sustainability indicators (Humpenöder et al. 2017) and increase in the population at risk of hunger well above 100 million (Fujimori et al. 2018a; Hasegawa et al. 2018b).

7.2.4 Risks arising from hazard, exposure and vulnerability

Table 7.1 shows hazards from land-climate-society interactions identified in previous chapters, or in other IPCC reports (with supplementary hazards appearing in the Appendix); the regions that are exposed or will be exposed to these hazards; components of the land-climate systems and societies that are vulnerable to the hazard; the risk associated with these impacts and the available indicative policy responses. The last column shows representative supporting literature.

Included are forest dieback, extreme events in multiple economic and agricultural regimes (also see Sections 7.2.2.1 and 7.2.2.2), disruption in flow regimes in river systems, climate change mitigation impacts (Section 7.2.3.2), competition for land (plastic substitution by cellulose, charcoal production), land degradation and desertification (Section 7.2.2.8), loss of carbon sinks, permafrost destabilisation (Section 7.2.2.7), and stranded assets (Section 7.3.4). Other hazards such as from failure of carbon storage, renewable energy impacts on land use, wild-fire in forest-urban transition context, extreme events effects on cultural heritage and urban air pollution from surrounding land use are covered in Table 7.1 extension in the appendix as well in Section 7.5.6.

Table 7.1 | Characterising land–climate risk and indicative policy responses. Table shows hazards from land–climate–society interactions identified in previous chapters or in *other* IPCC reports; the regions that are exposed or will be exposed to these hazards; components of the land-climate systems and societies that are vulnerable to the hazard; the risk associated with these impacts and the available policy responses and response options from Chapter 6. The last column shows representative supporting literature.

Land–climate–society interaction hazard	Exposure	Vulnerability	Risk	Policy response (indicative)	References
Forest dieback	Widespread across biomes and regions	Marginalised population with insecure land tenure	– Loss of forest-based livelihoods – Loss of identity	– Land rights – Community-based conservation – Enhanced political enfranchisement – Manager–scientist partnerships for adaptation silviculture	Allen et al. 2010; McDowell and Allen 2015; Sunderlin et al. 2017; Belcher et al. 2005; Soizic et al. 2013; Nagel et al. 2017
		Endangered species and ecosystems	– Extinction – Loss of ecosystem services (ES) – Cultural loss	– Effective enforcement of protected areas and curbs on illegal trade – Ecosystem restoration – Protection of indigenous people	Bailis et al. 2015; Cameron et al. 2016
Extreme events in multiple economic and agricultural regimes	Global	– Food-importing countries – Low-income indebtedness – Net food buyer	– Conflict – Migration – Food inflation – Loss of life – Disease, malnutrition – Farmer distress	– Insurance – Social protection encouraging diversity of sources – Climate smart agriculture – Land rights and tenure – Adaptive public distribution systems	Fraser et al. 2005; Schmidhuber and Tubiello 2007; Lipper et al. 2014a; Lunt et al. 2016; Tigchelaar et al. 2018; Casellas Connors and Janetos 2016
Disruption of flow regimes in river systems	– 1.5 billion people, Regional (e.g., South Asia, Australia) – Aral sea and others	– Water-intensive agriculture – Freshwater, estuarine and near coastal ecosystems – Fishers – Endangered species and ecosystems	– Loss of livelihoods and identity – Migration – Indebtedness	– Build alternative scenarios for economies and livelihoods based on non-consumptive use (e.g., wild capture fisheries) – Define and maintain ecological flows in rivers for target species and ES – Experiment with alternative, less water-consuming crops and water management strategies – Redefine SDGs to include freshwater ecosystems or adopt alternative metrics of sustainability Based on Nature's Contributions to People (NCP)	Craig 2010; Di Baldassarre et al. 2013; Verma et al. 2009; Ghosh et al. 2016; Higgins et al. 2018; Hall et al. 2013; Youn et al. 2014

Land–climate–society interaction hazard	Exposure	Vulnerability	Risk	Policy response (indicative)	References
Depletion/exhaustion of groundwater	– Widespread across semi-arid and humid biomes – India, China and the USA – Small Islands	– Farmers, drinking water supply – Irrigation – See forest note above – Agricultural production – Urban sustainability (Phoenix, US) – Reduction in dry-season river flows – Sea level rise	– Food insecurity – Water insecurity – Distress migration – Conflict – Disease – Inundation of coastal regions, estuaries and deltas	– Monitoring of emerging groundwater-climate linkages – Adaptation strategies that reduce dependence on deep groundwater – Regulation of groundwater use – Shift to less water-intensive rainfed crops and pasture – Conjunctive use of surface and groundwater	Wada et al. 2010; Rodell et al. 2009; Taylor et al. 2013; Aeschbach-Hertig and Gleeson 2012
Climate change mitigation impacts	Across various biomes, especially semi-arid and aquatic, where renewable energy projects (solar, biomass, wind and small hydro) are sited	– Fishers and pastoralists – Farmers – Endangered range restricted species and ecosystems	– Extinction of species – Downstream loss of ES – Loss of livelihoods and identity of fisher/pastoralist communities – Loss of regional food security	– Avoidance and informed siting in priority basins – Mitigation of impacts – Certification	Zomer et al. 2008; Nyong et al. 2007; Pielke et al. 2002; Schmidhuber and Tubiello 2007; Jumani et al. 2017; Eldridge et al. 2011; Bryan et al. 2010; Scarlat and Dallemand 2011
Competition for land e.g., plastic substitution by cellulose, charcoal production	Peri-urban and rural areas in developing countries	– Rural landscapes; farmers; charcoal suppliers; small businesses	– Land degradation; loss of ES; GHG emissions; lower adaptive capacity	– Sustainability certification; producer permits; subsidies for efficient kilns	Woollen et al. 2016; Kiruki et al. 2017a
Land degradation and desertification	Arid, semi-arid and sub-humid regions	– Farmers – Pastoralists – Biodiversity	– Food insecurity – Drought – Migration – Loss of agro and wild biodiversity	– Restoration of ecosystems and management of invasive species – Climate smart agriculture and livestock management – Managing economic impacts of global and local drivers – Changes in relief and rehabilitation policies – Land degradation neutrality	Fleskens, Luuk, Stringer 2014; Lambin et al. 2001; Cowie et al. 2018a; Few and Tebboth 2018; Sandstrom and Juhola 2017
Loss of carbon sinks	Widespread across biomes and regions	– Tropical forests – Boreal soils	– Feedback to global and regional climate change	– Conservation prioritisation of tropical forests – Afforestation	Barnett et al. 2005; Tribbia and Moser 2008
Permafrost destabilisation	Arctic and Sub-Arctic regions	– Soils – Indigenous communities – Biodiversity	– Enhanced GHG emissions	– Enhanced carbon uptake from novel ecosystem after thaw – Adapt to emerging wetlands	Schuur et al. 2015
Stranded assets	– Economies transitioning to low-carbon pathways – Oil economies – Coastal regions facing inundation	– Coal-based power – Oilrefineries – Plastic industry – Large dams – Coastal infrastructure	– Disruption of regional economies and conflict – Unemployment – Pushback against renewable energy – Migration	– Insurance and tax cuts – Long-term power purchase agreements – Economic and technical support for transitioning economies – transforming oil wealth into renewable energy leadership – Redevelopment using adaptation – OPEC investment in information sharing for transition	Farfan and Breyer 2017; Ansar et al. 2013; Van de Graaf 2017; Trieb et al. 2011

7.3 Consequences of climate – land change for human well-being and sustainable development

To further explore what is at stake for human systems, this section assesses literature about potential consequences of climate and land change for human well-being and ecosystems upon which humans depend. Risks described in Section 7.2 have significant social, spiritual, and economic ramifications for societies across the world and this section explores potential implications of the risks outlined above to food security, livelihood systems, migration, ecosystems, species, infectious disease, and communities and infrastructure. Because food and livelihood systems are deeply tied to one another, combinations of climate and land change could pose higher present risks to humans and ecosystems than examination of individual elements alone might suggest.

7.3.1 What is at stake for food security?

This section examines risks to food security when access to food is jeopardised by yield shortfall and instability related to climate stressors. Past assessments of climate change impacts have sometimes assumed that, when grain and food yields in one area of the world are lower than expected, world trade can redistribute food adequately to ensure food security. There is *medium confidence* that severe and spatially extensive climatic stressors pose *high risk* to stability of and access to food for large numbers of people across the world.

The 2007–2008, and 2010–2011 droughts in several regions of the world resulted in crop yield decline that in turn led some governments to protect their domestic grain supplies rather than engaging in free trade to offset food shortfalls in other areas of the world. These responses cascaded and strongly affected regional and global food prices. Simultaneous crop yield impacts combined with trade impacts have proven to play a larger and more pervasive role in global food crises than previously thought (Sternberg 2012, 2017; Bellemare 2015; Chatzopoulos et al. 2019). There is *high confidence* that regional climate extremes already have significant negative domestic and international economic impacts (Chatzopoulos et al. 2019).

7.3.2 Risks to where and how people live: Livelihood systems and migration

There is *high confidence* that climate and land change interact with social, economic, political, and demographic factors that affect how well and where people live (Sudmeier-Rieux et al. 2017; Government Office for Science 2011; Laczko and Piguet 2014; Bohra-Mishra and Massey 2011; Raleigh et al. 2015; Warner and Afifi 2011; Hugo 2011; Warner et al. 2012). There is *high evidence and high agreement* that people move to manage risks and seek opportunities for their safety and livelihoods, recognising that people respond to climatic change and land-related factors in tandem with other variables (Hendrix and Salehyan 2012; Lashley and Warner 2015; van der Geest and Warner 2014; Roudier et al. 2014; Warner and Afifi 2014; McLeman 2013; Kaenzig and Piguet 2014; Internal Displacement Monitoring Centre 2017; Warner 2018; Cohen and Bradley 2010; Thomas and Benjamin 2017). People move towards areas offering safety and livelihoods such as in rapidly growing settlements in coastal zones (Black et al. 2013; Challinor et al. 2017; Adger et al. 2013); burgeoning urban areas also face changing exposure to combinations of storm surges and sea level rise, coastal erosion and soil and water salinisation, and land subsidence (Geisler and Currens 2017; Maldonado et al. 2014; Bronen and Chapin 2013).

There is *medium confidence* that livelihood-related migration can accelerate in the short-to-medium term when weather-dependent livelihood systems deteriorate in relation to changes in precipitation, changes in ecosystems, and land degradation and desertification (Abid et al. 2016; Scheffran et al. 2012; Fussell et al. 2014; Bettini and Gioli 2016; Reyer et al. 2017; Warner and Afifi 2014; Handmer et al. 2012; Nawrotzki and Bakhtsiyarava 2017; Nawrotzki et al. 2016; Steffen et al. 2015; Black et al. 2013). Slow onset climate impacts and risks can exacerbate or otherwise interact with social conflict corresponding with movement at larger scales (see Section 7.2.3.2). Long-term deterioration in habitability of regions could trigger spatial population shifts (Denton et al. 2014).

There is *medium evidence* and *medium agreement* that climatic stressors can worsen the complex negative impacts of strife and conflict (Schleussner et al. 2016; Barnett and Palutikof 2014; Scheffran et al. 2012). Climate change and human mobility could be a factor that heightens tensions over scarce strategic resources, a further destabilising influence in fragile states experiencing socio-economic and political unrest (Carleton and Hsiang 2016a). Conflict and changes in weather patterns can worsen conditions for people working in rainfed agriculture or subsistence farming, interrupting production systems, degrading land and vegetation further (Papaioannou 2016; Adano and Daudi 2012). In recent decades, droughts and other climatic stressors have compounded livelihood pressures in areas already torn by strife (Tessler et al. 2015; Raleigh et al. 2015), such as in the Horn of Africa. Seizing of agricultural land by competing factions, preventing food distribution in times of shortage have, in this region and others, contributed to a triad of food insecurity, humanitarian need, and large movements of people (Theisen et al. 2011; Mohmmed et al. 2018; Ayeb-Karlsson et al. 2016; von Uexkull et al. 2016; Gleick 2014; Maystadt and Ecker 2014). People fleeing complex situations may return if peaceful conditions can be established. Climate change and development responses induced by climate change in countries and regions are likely to exacerbate tensions over water and land, and its impact on agriculture, fisheries, livestock and drinking water downstream. Shared pastoral landscapes used by disadvantaged or otherwise vulnerable communities are particularly impacted on by conflicts that are likely to become more severe under future climate change (Salehyan and Hendrix 2014; Hendrix and Salehyan 2012). Extreme events could considerably enhance these risks, in particular long-term drying trends (Kelley et al. 2015; Cutter et al. 2012a). There is *medium evidence* and *medium agreement* that governance is key in magnifying or moderating climate change impact and conflict (Bonatti et al. 2016).

There is *low evidence* and *medium agreement* that longer-term deterioration in the habitability of regions could trigger spatial population shifts (Seto 2011). Heat waves, rising sea levels that salinise and inundate coastal and low-lying aquifers and soils, desertification, loss of geologic sources of water such as glaciers and freshwater aquifers could affect many regions of the world and put life-sustaining ecosystems under pressure to support human populations (Flahaux and De Haas 2016; Chambwera et al. 2015; Tierney et al. 2015; Lilleør and Van den Broeck 2011).

7.3.3 Risks to humans from disrupted ecosystems and species

Risks of loss of biodiversity and ecosystem services (ES)

Climate change poses significant threat to species survival, and to maintaining biodiversity and ES. Climate change reduces the functionality, stability, and adaptability of ecosystems (Pecl et al. 2017). For example, drought affects cropland and forest productivity and reduces associated harvests (provisioning services). In additional, extreme changes in precipitation may reduce the capacity of forests to provide stability for groundwater (regulation and maintenance services). Prolonged periods of high temperature may cause widespread death of trees in tropical mountains, boreal and tundra forests, impacting on diverse ES, including aesthetic and cultural services (Verbyla 2011; Chapin et al. 2010; Krishnaswamy et al. 2014). According to the Millennium Ecosystem Assessment (2005), climate change is likely to become one of the most significant drivers of biodiversity loss by the end of the century.

There is *high confidence* that climate change already poses a moderate risk to biodiversity, and is projected to become a progressively widespread and high risk in the coming decades; loss of Arctic sea ice threatens biodiversity across an entire biome and beyond; the related pressure of ocean acidification, resulting from higher concentrations of carbon dioxide in the atmosphere, is also already being observed (UNEP 2009). There is ample evidence that climate change and land change negatively affects biodiversity across wide spatial scales. Although there is relatively *limited evidence* of current extinctions caused by climate change, studies suggest that climate change could surpass habitat destruction as the greatest global threat to biodiversity over the next several decades (Pereira et al. 2010). However, the multiplicity of approaches and the resulting variability in projections make it difficult to get a clear picture of the future of biodiversity under different scenarios of global climatic change (Pereira et al. 2010). Biodiversity is also severely impacted on by climate change induced land degradation and ecosystem transformation (Pecl et al. 2017). This may affect humans directly and indirectly through cascading impacts on ecosystem function and services (Millennium Assessment 2005). Climate change related human migration is likely to impact on biodiversity as people move into and contribute to land stress in biodiversity hotspots now and in the future; and as humans concurrently move into areas where biodiversity is also migrating to adapt to climate change (Oglethorpe et al. 2007).

Climate and land change increases risk to respiratory and infectious disease

In addition to risks related to nutrition articulated in Figure 7.1, human health can be affected by climate change through extreme heat and cold, changes in infectious diseases, extreme events, and land cover and land use (Hasegawa et al. 2016; Ryan et al. 2015; Terrazas et al. 2015; Kweka et al. 2016; Yamana et al. 2016). Evidence indicates that action to prevent the health impacts of climate change could provide substantial economic benefits (Martinez et al. 2015; Watts et al. 2015).

Climate change exacerbates air pollution with increasing UV and ozone concentration. It has negative impacts on human health and increases the mortality rate, especially in urban region (Silva et al. 2016, 2013; Lelieveld et al. 2013; Whitmee et al. 2015; Anenberg et al. 2010). In the Amazon, research shows that deforestation (both net loss and fragmentation) increases malaria, where vectors are expected to increase their home range (Alimi et al. 2015; Ren et al. 2016), confounded with multiple factors, such as social-economic conditions and immunity (Tucker Lima et al. 2017; Barros and Honório 2015). Deforestation has been shown to enhance the survival and development of major malaria vectors (Wang et al. 2016). The World Health Organization estimates 60,091 additional deaths for climate change induced malaria for the year 2030 and 32,695 for 2050 (World Health Organization 2014).

Human encroachment on animal habitat, in combination with the bushmeat trade in Central African countries, has contributed to the increased incidence of zoonotic (i.e., animal-derived) diseases in human populations, including the Ebola virus epidemic (Alexander et al. 2015a; Nkengasong and Onyebujoh 2018). The composition and density of zoonotic reservoir populations, such as rodents, is also influenced by land use and climate change (*high confidence*) (Young et al. 2017a). The bushmeat trade in many regions of central and west African forests (particularly in relation to chimpanzee and gorilla populations) elevates the risk of Ebola by increasing human–animal contact (Harrod 2015).

7.3.4 Risks to communities and infrastructure

There is *high confidence* that policies and institutions which accentuate vicious cycles of poverty and ill-health, land degradation and GHG emissions undermine stability and are barriers to achieving climate-resilient sustainable development. There is *high confidence* that change in climate and land pose high periodic and sustained risk to the very young, those living in poverty, and ageing populations. Older people are particularly exposed, due to more restricted access to resources, changes in physiology, and the decreased mobility resulting from age, which may limit adaptive capacity of individuals and populations as a whole (Filiberto et al. 2010).

Combinations of food insecurity, livelihood loss related to degrading soils and ecosystem change, or other factors that diminish the habitability of where people live, disrupt social fabric and are currently detected in most regions of the world (Carleton and

Hsiang 2016b) There is *high confidence* that coastal flooding and degradation already poses widespread and rising future risk to infrastructure value and stranded infrastructure, as well as livelihoods made possible by urban infrastructure (Radhakrishnan et al. 2017; Pathirana et al. 2018; Pathirana et al. 2018; Radhakrishnan et al. 2018; EEA 2016; Pelling and Wisner 2012; Oke et al. 2017; Parnell and Walawege 2011; Uzun and Cete 2004; Melvin et al. 2017).

There is *high evidence* and *high agreement* that climate and land change pose a high risk to communities. Interdependent infrastructure systems, including electric power and transportation, are highly vulnerable and interdependent (Below et al. 2012; Adger et al. 2013; Pathirana et al. 2018; Conway and Schipper 2011; Caney 2014; Chung Tiam Fook 2017). These systems are exposed to disruption from severe climate events such as weather-related power interruptions lasting for hours to days (Panteli and Mancarella 2015). Increased magnitude and frequency of high winds, ice storms, hurricanes and heat waves have caused widespread damage to power infrastructure and also severe outages, affecting significant numbers of customers in urban and rural areas (Abi-Samra and Malcolm 2011).

Increasing populations, enhanced per capita water use, climate change, and allocations for water conservation are potential threats to adequate water availability. As climate change produces variations in rainfall, these challenges will intensify, evidenced by severe water shortages in recent years in Cape Town, Los Angeles, and Rio de Janeiro, among other places (Watts et al. 2018; Majumder 2015; Ashoori et al. 2015; Mini et al. 2015; Otto et al. 2015; Ranatunga et al. 2014; Ray and Shaw 2016; Gopakumar 2014) (Cross-Chapter Box 5 in Chapter 3).

Cross-Chapter Box 10 | Economic dimensions of climate change and land

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Sustainable land management (SLM) makes strong social and economic sense. Early action in implementing SLM for climate change adaptation and mitigation provides distinct societal advantages. Understanding the full scope of what is at stake from climate change presents challenges because of inadequate accounting of the degree and scale at which climate change and land interactions impact society, and the importance society places on those impacts (Santos et al. 2016) (Sections 7.2.2, 5.3.1, 5.3.2 and 4.1). The consequences of inaction and delay bring significant risks, including irreversible change and loss in land ecosystem services (ES) – including food security – with potentially substantial economic damage to many countries in many regions of the world (high confidence).

This cross-chapter box brings together the salient economic concepts underpinning the assessments of SLM and mitigation options presented in this report. Four critical concepts are required to help assess the social and economic implications of land-based climate action:

i. Value to society
ii. Damages from climate and land-induced interventions on land ecosystems
iii. Costs of action and inaction
iv. Decision-making under uncertainty

i. Value to society

Healthy functioning land and ecosystems are essential for human health, food and livelihood security. Land derives its value to humans from being a finite resource and vital for life, providing important ES from water recycling, food, feed, fuel, biodiversity and carbon storage and sequestration.

Many of these ES may be difficult to estimate in monetary terms, including when they hold high symbolic value, linked to ancestral history, or traditional and indigenous knowledge systems (Boillat and Berkes 2013). Such incommensurable values of land are core to social cohesion – social norms and institutions, trust that enables all interactions, and sense of community.

ii. Damages from climate and land-induced interventions on land ecosystems

Values of many land-based ES and their potential loss under land–climate change interaction can be considerable: in 2011, the global value of ES was 125 trillion USD per year and the annual loss due to land-use change was between 4.3 and 20.2 trillion USD per year from 2007 (Costanza et al. 2014; Rockström et al. 2009). The annual costs of land degradation are estimated to be about 231 billion USD per year or about 0.41% of the global GDP of 56.49 trillion USD in 2007 (Nkonya et al. 2016) (Sections 4.4.1 and 4.4.2).

Cross-Chapter Box 10 (continued)

Studies show increasingly negative effects on GDP from damage and loss to land-based values and service as global mean temperatures increase, although the impact varies across regions (Kompas et al. 2018).

iii. Costs of action and inaction

Evidence suggests that the cost of inaction in mitigation and adaptation, and land use, exceeds the cost of interventions in both individual countries, regions, and worldwide (Nkonya et al. 2016). Continued inaction reduces the future policy option space, dampens economic growth and increases the challenges of mitigation as well as adaptation (Moore and Diaz 2015; Luderer et al. 2013). The cost of reducing emissions is estimated to be considerably less than the costs of the damages at all levels (Kainuma et al. 2013; Moran 2011; Sánchez and Maseda 2016).

The costs of adapting to climate impacts are also projected to be substantial, although evidence is limited (summarised in Chambwera et al. 2014a). Estimates range from 9 to 166 billion USD per year at various scales and types of adaptation, from capacity building to specific projects (Fankhauser 2017). There is insufficient literature about the costs of adaptation in the agriculture or land-based sectors (Wreford and Renwick 2012) due to lack of baselines, uncertainty around biological relationships and inherent uncertainty about anticipated avoided damage estimates, but economic appraisal of actions to maintain the functions of the natural environment and land sector generate positive net present values (Adaptation Sub-committee 2013).

Preventing land degradation from occurring is considered more cost-effective in the long term compared to the magnitude of resources required to restore already degraded land (Cowie et al. 2018a) (Section 3.6.1). Evidence from drylands shows that each US dollar invested in land restoration provides between 3 and 6 USD in social returns over a 30-year period, using a discount rate between 2.5 and 10% (Nkonya et al. 2016). SLM practices reverse or minimise economic losses of land degradation, estimated at between 6.3 and 10.6 trillion USD annually, (ELD Initiative 2015) more than five times the entire value of agriculture in the market economy (Costanza et al. 2014; Fischer et al. 2017; Sandifer et al. 2015; Dasgupta et al. 2013) (Section 3.7.5).

Across other areas such as food security, disaster mitigation and risk reduction, humanitarian response, and healthy diet (to address malnutrition as well as disease), early action generates economic benefits greater than costs (*high evidence, high agreement*) (Fankhauser 2017; Wilkinson et al. 2018; Venton 2018; Venton et al. 2012; Clarvis et al. 2015; Nugent et al. 2018; Watts et al. 2018; Bertram et al. 2018) (Sections 6.3 and 6.4).

iv. Decision-making under uncertainty

Given that significant uncertainty exists regarding the future impacts of climate change, effective decisions must be made under unavoidable uncertainty (Jones et al., 2014).

Approaches that allow for decision-making under uncertainty are continually evolving (Section 7.5). An emerging trend is towards new frameworks that will enable multiple decision-makers with multiple objectives to explore the trade-offs between potentially conflicting preferences to identify strategies that are robust to deep uncertainties (Singh et al. 2015; Driscoll et al. 2016; Araujo Enciso et al. 2016; Herman et al. 2014; Pérez et al. 2016; Girard et al. 2015; Haasnoot et al. 2018; Roelich and Giesekam 2019).

Valuation of benefits and damages and costing interventions: Measurement issues

Cost appraisal tools for climate adaptation are many and their suitability depends on the context (Section 7.5.2.2). Cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) are commonly applied, especially for current climate variability situations. However, these tools are not without criticism and their limitations have been observed in the literature (see Rogelj et al. 2018). In general, measuring costs and providing valuations are influenced by four conditions: measurement and valuation; the time dimension; externalities; and aggregate versus marginal costs.

Measurement and value issues

ES not traded in the market fall outside the formal or market-based valuation and so their value is either not accounted for or underestimated in both private and public decisions (Atkinson et al. 2018). Environmental valuation literature uses a range of techniques to assign monetary values to environmental outcomes where no market exists (Atkinson et al. 2018; Dallimer et al. 2018), but some values remain inestimable. For some indigenous cultures and peoples, land is not considered something that can be sold and bought, so economic valuations are not meaningful even as proxy approaches (Boillat and Berkes 2013; Kumpula et al. 2011; Pert et al. 2015; Xu et al. 2005).

Cross-Chapter Box 10 (continued)

While a rigorous CBA is broader than a purely financial tool and can capture non-market values where they exist, it can prioritise certain values over others (such as profit maximisation for owners, efficiency from the perspective of supply chain processes, and judgements about which parties bear the costs). Careful consideration must be given to whose perspectives are considered when undertaking a CBA and also to the limitations of these methods for policy interventions.

Time dimension (short versus long term) and the issue of discount rates

Economics uses a mechanism to convert future values to present day values known as discounting, or the pure rate of time preference. Discount rates are increasingly being chosen to reflect concerns about intergenerational equity, and some countries (e.g., the UK and France) apply a declining discount rate for long-term public projects. The choice of discount rate has important implications for policy evaluation (Anthoff, Tol, and Yohe, 2010; Arrow et al., 2014; Baral, Keenan, Sharma, Stork, and Kasel, 2014; Dasgupta et al., 2013; Lontzek, Cai, Judd, and Lenton, 2015; Sorokin et al., 2015; van den Bergh and Botzen, 2014) (*high evidence, high agreement*). Stern (2007), for example, used a much lower discount rate (giving almost equal weight to future generations) than the mainstream authors (e.g., Nordhaus (1941) and obtained much higher estimates of the damage of climate change).

Positive and negative externalities (consequences and impacts not accounted for in market economy),

All land use generates externalities (unaccounted for side effects of an activity). Examples include loss of ES (e.g., reduced pollinators; soil erosion, increased water pollution, nitrification, etc.). Positive externalities include sequestration of carbon dioxide (CO_2) and improved soil water filtration from afforestation. Externalities can also be social (e.g., displacement and migration) and economic (e.g., loss of productive land). In the context of climate change and land, the major externality is the agriculture, forestry and other land-use (AFOLU) sourced greenhouse gas (GHG) emissions. Examples of mechanisms to internalise externalities are discussed in 7.5.

Aggregate versus marginal costs

Costs of climate change are often referred to through the marginal measure of the social cost of carbon (SCC), which evaluate the total net damages of an extra metric tonne of CO_2 emissions due to the associated climate change (Nordhaus 2014). The SCC can be used to determine a carbon price, but SCC depends on discount rate assumptions and may neglect processes, including large losses of biodiversity, political instability, violent conflicts, large-scale migration flows, and the effects of climate change on the development of economies (Stern 2013; Pezzey 2019).

At the sectoral level, marginal abatement cost (MAC) curves are widely used for the assessment of costs related to CO_2 or GHG emissions reduction. MAC measures the cost of reducing one more GHG unit and MAC curves are either expert-based or model-derived and offer a range of approaches and assumptions on discount rates or available abatement technologies (Moran 2011).

7.3.4.1 Windows of opportunity

Windows of opportunity are important learning moments wherein an event or disturbance in relation to land, climate, and food security triggers responsive social, political, policy change (*medium agreement*). Policies play an important role in windows of opportunity and are important in relation to managing risks of desertification, soil degradation, food insecurity, and supporting response options for SLM (*high agreement*) (Kivimaa and Kern 2016; Gupta et al. 2013b; Cosens et al. 2017; Darnhofer 2014; Duru et al. 2015) (Chapter 6).

A wide range of events or disturbances may initiate windows of opportunity – ranging from climatic events and disasters, recognition of a state of land degradation, an ecological social or political crisis, and a triggered regulatory burden or opportunity. Recognition of a degraded system such as land degradation and desertification (Chapters 3 and 4) and associated ecosystem feedbacks, allows for strategies, response options and policies to address the degraded state (Nyström et al. 2012). Climate related disasters (flood, droughts, etc.) and crisis may trigger latent local adaptive capacities leading to systemic equitable improvement (McSweeney and Coomes 2011), or novel and innovative recombining of sources of experience and knowledge, allowing navigation to transformative social ecological transitions (Folke et al. 2010). The occurrence of a series of punctuated crises such as floods or droughts, qualify as windows of opportunity when they enhance society's capacity to adapt over the long term (Pahl-Wostl et al. 2013). A disturbance from an ecological, social, or political crisis may be sufficient to trigger the emergence of new approaches to governance wherein there is a change in the rules of the social world such as informal agreements surrounding human activities or formal rules of public policies (Olsson et al. 2006; Biggs et al. 2017) (Section 7.6). A combination of socio-ecological changes may provide windows of opportunity for a socio-technical niche to be adopted on a greater scale, transforming practices towards SLM such as biodiversity-based agriculture (Darnhofer 2014; Duru et al. 2015).

Policy may also create windows of opportunity. A disturbance may cause inconvenience, including high costs of compliance with environmental regulations, thereby initiating a change of behaviour (Cosens et al. 2017). In a similar vein, multiple regulatory requirements existing at the time of a disturbance may result in emergent processes and novel solutions in order to correct for piecemeal regulatory compliance (Cosens et al. 2017). Lastly, windows of opportunity can be created by a policy mix or portfolio that provides for creative destruction of old social processes and thereby encourages new innovative solutions (Kivimaa et al. 2017b) (Section 7.4.8).

7.4 Policy instruments for land and climate

This section outlines policy responses to risk. It describes multi-level policy instruments (Section 7.4.1), policy instruments for social protection (Section 7.4.2), policies responding to hazard (Section 7.4.3), GHG fluxes (Section 7.4.4), desertification (Section 7.4.5), land degradation (Section 7.4.6), economic instruments (Section 7.4.7), enabling effective policy instruments through policy mixes (Section 7.4.8), and barriers to SLM and overcoming these barriers (Section 7.4.9).

Policy instruments are used to influence behaviour and effect a response – to do, not do, or continue to do certain things (Anderson 2010) – and they can be invoked at multiple levels (international, national, regional, and local) by multiple actors (Table 7.2). For efficiency, equity and effectiveness considerations, the appropriate choice of instrument for the context is critical and, across the topics addressed in this report, the instruments will vary considerably. A key consideration is whether the benefits of the action will generate private or public social net benefits. Pannell (2008) provides a widely-used framework for identifying the appropriate type of instrument depending on whether the actions encouraged by the instrument are private or public, and positive or negative. Positive incentives (such as financial or regulatory instruments) are appropriate where the public net benefits are highly positive and the private net benefits are close to zero. This is likely to be the case for GHG mitigation measures such as carbon pricing. Many other GHG mitigation measures (more effective water or fertiliser use, better agricultural practices, less food waste, agroforestry systems, better forest management) discussed in previous chapters may have substantial private as well as public benefit. Extension (knowledge provision) is recommended when public net benefits are *highly positive*, and private net benefits are *slightly positive* – again for some GHG mitigation measures, and for many adaptations, food security and SLM measures. Where the private net benefits are *slightly positive* but the public net benefits *highly negative*, negative incentives (such as regulations and prohibitions) are appropriate, (e.g., over-application of fertiliser).

While Pannell's (2008) framework is useful, it does not address considerations relating to the timescale of actions and their consequences, particularly in the long time-horizons involved under climate change: private benefits may accrue in the short term but become negative over time (Outka 2012) and some of the changes necessary will require transformation of existing systems (Park et al. 2012; Hadarits et al. 2017) necessitating a more comprehensive suite of instruments. Furthermore, the framework applies to private land ownership, so where land is in different ownership structures, different mechanisms will be required. Indeed, land tenure is recognised as a factor in barriers to sustainable land management and an important governance consideration (Sections 7.4.9 and 7.6.4). A thorough analysis of the implications of policy instruments temporally, spatially and across other sectors and goals (e.g., climate versus development) is essential before implementation to avoid unintended consequences and achieve policy coherence (Section 7.4.8).

7.4.1 Multi-level policy instruments

Policy responses and planning in relation to land and climate interactions occur at and across multiple levels, involve multiple actors, and utilise multiple planning mechanisms (Urwin and Jordan 2008). Climate change is occurring on a global scale while the impacts of climate change vary from region to region and even within a region. Therefore, in addressing local climate impacts, local governments and communities are key players. Advancing governance of climate change across all levels of government and relevant stakeholders is crucial to avoid policy gaps between local action plans and national/sub-national policy frameworks (Corfee-Morlot et al. 2009).

This section of the chapter identifies policies by level that respond to land and climate problems and risks. As risk management in relation to land and climate occurs at multiple levels by multiple actors, and across multiple sectors in relation to hazards (as listed on Table 7.2), risk governance, or the consideration of the landscapes of risk arising from Chapters 2 to 6 is addressed in Sections 7.5 and 7.6. Categories of instruments include regulatory instruments (command and control measures), economic and market instruments (creating a market, sending price signals, or employing a market strategy), voluntary of persuasive instruments (persuading people to internalise behaviour), and managerial (arrangements including multiple actors in cooperatively administering a resource or overseeing an issue) (Gupta et al. 2013a; Hurlbert 2018b).

Given the complex spatial and temporal dynamics of risk, a comprehensive, portfolio of instruments and responses is required to comprehensively manage risk. Operationalising a portfolio response can mean layering, sequencing or integrating approaches. Layering means that, within a geographical area, households are able to benefit from multiple interventions simultaneously (e.g., those for family planning and those for livelihoods development). A sequencing approach starts with those interventions that address the initial binding constraints, and then adding further interventions later (e.g., the poorest households first receive grant-based support before then gaining access to appropriate microfinance or market-oriented initiatives). Integrated approaches involve cross-sectoral support within the framework of one programme (Scott et al. 2016; Tengberg and Valencia 2018) (Sections 7.4.8, 7.5.6 and 7.6.3).

Climate-related risk could be categorised by climate impacts such as flood, drought, cyclone, and so on (Christenson et al. 2014). Table 7.2 outlines instruments relating to impacts responding to the risk of climate change, food insecurity, land degradation and desertification, and hazards (flood, drought, forest fire), and GHG fluxes (climate mitigation).

7.4.2 Policies for food security and social protection

There is *medium evidence* and *high agreement* that a combination of structural and non-structural policies are required in averting and minimising as well as responding to land and climate change risk, including food and livelihood security. If disruptions to elements of food security are long-lasting, policies are needed to change practices.

If disruptions to food and livelihood systems are temporary, then policies aimed at stemming worsening human well-being and stabilising short-term income fluctuations in communities (such as

Table 7.2 | Policies/instruments that address multiple land-climate risks at different jurisdictional levels.

Scale	Policy/instrument	Food security	Land degradation and desertification	Sustainable land management (SLM)	Climate related extremes	GHG flux/ climate change mitigation
Global/ cross-border	Finance mechanisms (also national)	●	●	●	●	●
	Certification (also national)		●	●		●
	Standards (including risk standards) (also national)		●	●	●	●
	Market-based systems (also national)			●		●
	Payments for ecosystem services (also national)		●	●	●	●
	Disaster assistance (also national)				●	
National	Taxes	●		●		●
	Subsidies	●	●	●		●
	Direct income payments (with cross-compliance)	●	●	●		●
	Border adjustments (e.g., tariffs)	●				●
	Grants	●	●	●	●	●
	Bonds	●	●	●		●
	Forecast-based finance, targeted microfinance	●	●	●		●
	Insurance (various forms)	●			●	
	Hazard information and communication (also sub-national and local)	●			●	
	Drought preparedness plans (also sub-national and local)	●			●	
	Fire policy (suppression or prescribed fire management)			●	●	●
	Regulations	●	●	●	●	●
	Land ownership laws (reform of, if necessary, for secure land title, or access/control)	●	●	●		
	Protected area designation and management		●	●		
	Extension – including skill and community development for livelihood diversification (also sub-national and local)	●	●	●	●	●
Sub-national	Spatial and land-use planning	●	●		●	
	Watershed management	●	●			
Local	Land-use zoning, spatial planning and integrated land-use planning	●		●	●	
	Community-based awareness programmes	●	●	●	●	●

This table highlights policy and instruments addressing key themes identified in this chapter; a "●" indicates the relevance of the policy or instrument to the corresponding theme.

increasing rural credit or providing social safety-net programmes) may be appropriate (Ward 2016).

7.4.2.1 Policies to ensure availability, access, utilisation and stability of food

Food security is affected by interactions between climatic factors (rising temperatures, changes in weather variability and extremes), changes in land use and land degradation, and Socio-economic Pathways and policy choices related to food systems (see Figures 7.1 and 7.2). As outlined in Chapter 5, key aspects of food security are food availability, access to food, utilisation of food, and stability of food systems.

While comprehensive reviews of policy are rare and additional data is needed (Adu et al. 2018), evidence indicates that the results of food security interventions vary widely due to differing values underlying the design of instruments. A large portfolio of measures is available to shape outcomes in these areas from the use of tariffs or subsidies, to payments for production practices (OECD 2018). In the past, efforts to increase food production through significant investment in agricultural research, including crop improvement, have benefited farmers by increasing yields and reducing losses, and have helped consumers by lowering food prices (Pingali 2012, 2015; Alston and Pardey 2014; Popp et al. 2013). Public spending on agriculture research and development (R&D) has been more effective at raising sustainable agriculture productivity than irrigation or fertiliser subsidies (OECD 2018). Yet, on average, between 2015 and 2017, governments spent only around 14% of total agricultural support on services, including physical and knowledge infrastructure, transport and information and communications technology.

In terms of increasing food availability and supply, producer support, including policies mandating subsidies or payments, have been used to boost production of certain commodities or protect ES. Incentives can distort markets and farm business decisions in both negative and positive ways. For example, the European Union promotes meat and dairy production through voluntary coupled direct payments. These do not yet internalise external damage to climate, health, and groundwater (Velthof et al. 2014; Bryngelsson et al. 2016). In most countries, producer support has been declining since the mid-1990s (OECD 2018). Yet new evidence indicates that a government policy supporting producer subsidy could encourage farmers to adopt new technologies and reduce GHG emissions in agriculture (*medium evidence*, *high agreement*). However, this will require large capital (Henderson 2018). Since a 1995 reform in its forest law, Costa Rica has effectively used a combination of fuel tax, water tax, loans and agreements with companies, to pay landowners for agroforestry, reforestation and sustainable forest management (Porras and Asquith 2018).

Inland capture fisheries and aquaculture are an integral part of nutrition security and livelihoods for large numbers of people globally (Welcomme et al. 2010; Hall et al. 2013; Tidwell and Allan 2001; Youn et al. 2014) and are increasingly vulnerable to climate change and competing land and water use (Allison et al. 2009; Youn et al. 2014). Future production may increase in some high-latitude regions (*low confidence*) but production is likely to decline in low-latitude regions under future warming (*high confidence*) (Brander and Keith 2015; Brander 2007). However over-exploitation and degradation of rivers has resulted in a decreasing trend in the contribution of capture fisheries to protein security in comparison to managed aquaculture (Welcomme et al. 2010). Aquaculture, however, competes for land and water resources with many negative ecological and environmental impacts (Verdegem and Bosma 2009; Tidwell and Allan 2001). Inland capture fisheries are undervalued in national and regional food security, ES and economy, are data deficient and are neglected in terms of supportive policies at national levels, and absent in SDGs (Cooke et al. 2016; Hall et al. 2013; Lynch et al. 2016). Revival of sustainable capture fisheries and converting aquaculture to environmentally less-damaging management regimes, is likely to succeed with the following measures: investment in recognition of their importance, improved valuation and assessment, secure tenure and adoption of social, ecological and technological guidelines, upstream-downstream river basin cooperation, and maintenance of ecological flow regimes in rivers (Youn et al. 2014; Mostert et al. 2007; Ziv et al. 2012; Hurlbert and Gupta 2016; Poff et al. 2003; Thomas 1996; FAO 2015a).

Extension services, and policies supporting agricultural extension systems, are also critical. Smallholder farmer-dominated agriculture is currently the backbone of global food security in the developing world. Without education and incentives to manage land and forest resources in a manner that allows regeneration of both the soils and wood stocks, smallholder farmers tend to generate income through inappropriate land management practices, engage in agricultural production on unsuitable land and use fertile soils, timber and firewood for brick production and construction. Also, they engage in charcoal production (deforestation) as a coping mechanism (increasing income) against food deficiency (Munthali and Murayama 2013). Through extension services, governments can play a proactive role in providing information on climate and market risks, animal and plant health. Farmers with greater access to extension training retain more crop residues for mulch on their fields (Jaleta et al. 2015, 2013; Baudron et al. 2014).

Food security cannot be achieved by increasing food availability alone. Policy instruments, which increase access to food at the household level, include safety-net programming and universal basic income. The graduation approach, developed and tested over the past decade using randomised control trials in six countries, has lasting positive impacts on income, as well as food and nutrition security (Banerjee et al. 2015; Raza and Poel 2016) (*robust evidence*, *high agreement*). The graduation approach layers and integrates a series of interventions designed to help the poorest: consumption support in the form of cash or food assistance, transfer of an income-generating asset (such as a livestock) and training on how to maintain the asset, assistance with savings and coaching or mentoring over a period of time to reinforce learning and provide support. Due to its success, the graduation approach is now being scaled up, and is now used in more than 38 countries and included by an increasing number of governments in social safety-net programmes (Hashemi and de Montesquiou 2011).

At the national and global levels, food prices and trade policies impact on access to food. Fiscal policies, such as taxation, subsidies, or tariffs, can be used to regulate production and consumption of certain foods and can affect environmental outcomes. In Denmark, a tax on saturated fat content of food adopted to encourage healthy eating habits accounted for 0.14% of total tax revenues between 2011 and 2012 (Sassi et al. 2018). A global tax on GHG emissions, for example, has large mitigation potential and will generate tax revenues, but may also result in large reductions in agricultural production (Henderson 2018). Consumer-level taxes on GHG-intensive food may be applied to address competitiveness issues between different countries, if some countries use taxes while others do not. However, increases in prices might impose disproportionate financial burdens on low-income households, and may not be publicly acceptable. A study examining the relationship between food prices and social unrest found that, between 1990 and 2011, whereas food price stability has not been associated with increases in social unrest (Bellemare 2015).

Interventions that allow people to maximise their productive potential while protecting the ES may not ensure food security in all contexts. Some household land holdings are so small that self-sufficiency is not possible (Venton 2018). Value chain development has, in the past, increased farm income but delivered fewer benefits to vulnerable consumers (Bodnár et al. 2011). Ultimately, a mix of production activities and consumption support is needed. Consumption support can be used to help achieve the second important element of food security – access to food.

Agricultural technology transfer can help optimise food and nutrition security (Section 7.4.4.3). Policies that affect agricultural innovation span sectors and include 'macro-economic policy-settings; institutional governance; environmental standards; investment, land, labor and education policies; and incentives for investment, such as a predictable regulatory environment and robust intellectual property rights'.

The scientific community can partner across sectors and industries for better data sharing, integration, and improved modelling and analytical capacities (Janetos et al. 2017; Lunt et al. 2016). To better predict, respond to, and prepare for concurrent agricultural failures, and gain a more systematic assessment of exposure to agricultural climate risk, large data gaps need to be filled, as well as gaps in empirical foundation and analytical capabilities (Janetos et al. 2017; Lunt et al. 2016). Data required include global historical datasets, many of which are unreliable, inaccessible, or not available (Maynard 2015; Lunt et al. 2016). Participation in co-design for scenario planning can build social and human capital while improving understanding of food system risks and creating innovative ways for collectively planning for a more equitable and resilient food system (Himanen et al. 2016; Meijer et al. 2015; Van Rijn et al. 2012).

Demand management for food, including promoting healthy diets, reducing food loss and waste, is covered in Chapter 5. There is a gap in knowledge regarding what policies and instruments support demand management. There is *robust evidence* and *robust agreement* that changes in household wealth and parents' education can drive changes in diet and improvements in nutrition (Headey et al. 2017). Bangladesh has managed to sustain a rapid reduction in the rate of child undernutrition for at least two decades. Rapid wealth accumulation and large gains in parental education are the two largest drivers of change (Headey et al. 2017). Educating consumers, and providing affordable alternatives, will be critical to changing unsustainable food-use habits relevant to climate change.

7.4.2.2 Policies to secure social protection

There is *medium evidence* and *high agreement* from all regions of the world that safety nets and social protection schemes can provide stability which prevents and reduces abject poverty (Barrientos 2011; Hossain 2018; Cook and Pincus 2015; Huang and Yang 2017; Slater 2011; Sparrow et al. 2013; Rodriguez-Takeuchi and Imai 2013; Bamberg et al. 2018) in the face of climatic stressors and land change (Davies et al. 2013; Cutter et al. 2012b; Pelling 2011; Ensor 2011).

The World Bank estimates that, globally, social safety net transfers have reduced the absolute poverty gap by 45% and the relative poverty gap by 16% (World Bank 2018). Adaptive social protection builds household capacity to deal with shocks as well as the capacity of social safety nets to respond to shocks. For low-income communities reliant on land and climate for their livelihoods and well-being, social protection provides a way for vulnerable groups to manage weather and climatic variability and deteriorating land conditions to household income and assets (*robust evidence*, *high agreement*) (Baulch et al. 2006; Barrientos 2011; Harris 2013; Fiszbein et al. 2014; Kiendrebeogo et al. 2017; Kabeer et al. 2010; FAO 2015b; Warner et al. 2018; World Bank 2018).

A lifecycle approach to social protection is one approach, which some countries (such as Bangladesh) are using when developing national social protection policies. These policies acknowledge that households face risks across the lifecycle that they need to be protected from. If shocks are persistent, or occur numerous times, then policies can address concerns of a more structural nature (Glauben et al. 2012). Barrett (2005), for example, distinguishes between the role of safety nets (which include programmes such as emergency feeding programmes, crop or unemployment insurance, disaster assistance, etc.) and cargo nets (which include land reforms, targeted microfinance, targeted school food programmes, etc.). While the former prevents non-poor and transient poor from becoming chronically poor, the latter is meant to lift people out of poverty by changing societal or institutional structures. The graduation approach has adopted such systematic thinking with successful results (Banerjee et al. 2015).

Social protection systems can provide buffers against shocks through vertical or horizontal expansion, 'piggybacking' on pre-established programmes, aligning social protection and humanitarian systems or refocusing existing resources (Wilkinson et al. 2018; O'Brien et al. 2018; Jones and Presler-Marshall 2015). There is increasing evidence that forecast-based financing, linked to a social protection, can be used to enable anticipatory actions based on forecast triggers, and guarantee funding ahead of a shock (Jjemba et al. 2018). Accordingly, scaling up social protection based on an early warning could enhance timeliness, predictability and adequacy of social protection benefits (Kuriakose et al. 2012; Costella et al. 2017a; Wilkinson et al. 2018; O'Brien et al. 2018).

Countries at high risk of natural disasters often have lower safety-net coverage percent (World Bank 2018), and there is *medium evidence* and *medium agreement* that those countries with few financial and other buffers have lower economic and social performance (Cutter et al. 2012b; Outreville 2011a). Social protection systems have also been seen as an unaffordable commitment of public budget in many developing and low-income countries (Harris 2013). National systems may be disjointed and piecemeal, and subject to cultural acceptance and competing political ideologies (Niño-Zarazúa et al. 2012). For example, Liberia and Madagascar each have five different public works programmes, each with different donor organisations and different implementing agencies (Monchuk 2014). These implementation shortcomings mean that positive effects of social protection systems might not be robust enough to shield recipients completely against the impacts of severe shocks or from long-term losses and damages from climate change (*limited evidence*, *high agreement*) (Davies et al. 2009; Umukoro 2013; Béné et al. 2012; Ellis et al. 2009).

There is increasing support for establishment of public-private safety nets to address climate-related shocks, which are augmented by proactive preventative (adaptation) measures and related risk transfer instruments that are affordable to the poor (Kousky et al. 2018b). Studies suggest that the adaptive capacity of communities has improved with regard to climate variability, like drought, when ex-ante tools, including insurance, have been employed holistically; providing insurance in combination with early warning and institutional and policy approaches reduces livelihood and food insecurity as well as strengthens social structures (Shiferaw et al. 2014; Lotze-Campen and Popp 2012). Bundling insurance with early warning and seasonal forecasting can reduce the cost of insurance premiums (Daron and Stainforth 2014). The regional risk insurance scheme, African Risk Capacity, has the potential to significantly reduce the cost of insurance premiums (Siebert 2016) while bolstering contingency planning against food insecurity.

Work-for-insurance programmes applied in the context of social protection have been shown to improve livelihood and food security in Ethiopia (Berhane 2014; Mohmmed et al. 2018) and Pakistan. The R4 Rural Resilience Initiative in Ethiopia is a widely cited example of a programme that serves the most vulnerable and includes aspects of resource management, and access by the poor to financial services, including insurance and savings (Linnerooth-Bayer et al. 2018). Weather index insurance (such as index-based crop insurance) is being presented to low-income farmers and pastoralists in developing countries (e.g., Ethiopia, India, Kazakhstan, South Asia) to complement informal risk sharing, reducing the risk of lost revenue associated with variations in crop yield, and provide an alternative to classic insurance (Bogale 2015a; Conradt et al. 2015; Dercon et al. 2014; Greatrex et al. 2015; McIntosh et al. 2013). The ability of insurance to contribute to adaptive capacity depends on the overall risk management and livelihood context of households – studies find that agriculturalists and foresters working on rainfed farms/land with more years of education and credit but limited off-farm income are more willing to pay for insurance than households who have access to remittances (such as from family members who have migrated) (Bogale 2015a; Gan et al. 2014; Hewitt et al. 2017; Nischalke 2015). In Europe, modelling suggests that insurance incentives, such as vouchers, would be less expensive than total incentivised damage reduction and may reduce residential flood risk in Germany by 12% in 2016 and 24% by 2040 (Hudson et al. 2016).

7.4.3 Policies responding to climate-related extremes

7.4.3.1 Risk management instruments

Risk management addressing climate change has broadened to include mitigation, adaptation and disaster preparedness in a process using instruments facilitating contingency and cross-sectoral planning (Hurlimann and March 2012; Oels 2013), social community planning, and strategic, long-term planning (Serrao-Neumann et al. 2015a). A comprehensive consideration integrates principles from informal support mechanisms to enhance formal social protection programming (Mobarak and Rosenzweig 2013; Stavropoulou et al. 2017) such that the social safety net, disaster risk management, and climate change adaptation are all considered to enhance livelihoods of the chronic poor (see char dwellers and recurrent floods in Jamuna and Brahmaputra basins of Bangladesh Awal 2013) (Section 7.4.7). Iterative risk management is an ongoing process of assessment, action, reassessment and response (Mochizuki et al. 2015) (Sections 7.5.2 and 7.4.7.2).

Important elements of risk planning include education, and creation of hazard and risk maps. Important elements of predicting include hydrological and meteorological monitoring to forecast weather, seasonal climate forecasts, aridity, flood and extreme weather. Effective responding requires robust communication systems that pass on information to enable response (Cools et al. 2016).

Gauging the effectiveness of policy instruments is challenging. Timescales may influence outcomes. To evaluate effectiveness researchers, programme managers and communities strive to develop consistency, comparability, comprehensiveness and coherence in their tracking. In other words, practitioners utilise a consistent and operational conceptualisation of adaptation; focus on comparable units of analysis; develop comprehensive datasets on adaptation action; and are coherent with an understanding of what constitutes real adaptation (Ford and Berrang-Ford 2016). Increasing the use of systematic reviews or randomised evaluations may also be helpful (Alverson and Zommers 2018).

Many risk management policy instruments are referred to by the International Organization of Standardization which lists risk management principles, guidelines, and frameworks for explaining the elements of an effective risk management programme (ISO 2009). The standard provides practical risk management instruments and makes a business case for risk management investments (McClean et al. 2010). Insurance addresses impacts associated with extreme weather events (storms, floods, droughts, temperature extremes), but it can provide disincentives for reducing disaster risk at the local level through the transfer of risk spatially to other places or temporally to the future (Cutter et al. 2012b) and uptake is unequally distributed across regions and hazards (Lal et al. 2012). Insurance instruments (Sections 7.4.2 and 7.4.6) can take many forms (traditional indemnity based, market-based crop insurance, property insurance), and some are linked to livelihoods sensitive to weather as well as food security (linked to social safety-net programmes) and ecosystems (coral reefs and mangroves). Insurance instruments can also provide a framework for risk signals to adaptation planning and implementation and facilitate financial buffering when climate impacts exceed current capabilities delivered through both public and private finance (Bogale 2015b; Greatrex et al. 2015; Surminski et al. 2016). A holistic consideration of all instruments responding to extreme impacts of climate change (drought, flood, etc.) is required when assessing if policy instruments are promoting livelihood capitals and contributing to the resilience of people and communities (Hurlbert 2018b). This holistic consideration of policy instruments leads to a consideration of risk governance (Section 7.6).

Early warning systems are critical policy instruments for protecting lives and property, adapting to climate change, and effecting adaptive climate risk management (*high confidence*) (Selvaraju 2011; Cools et al. 2016; Travis 2013; Henriksen et al. 2018; Seng 2013; Kanta Kafle 2017; Garcia and Fearnley 2012). Early warning systems exist at different levels and for different purposes, including the Food and Agriculture Organization of the United Nations' Global Information and Early Warning System on Food and Agriculture (GIEWS), United States Agency for International Development (USAID) Famine Early Warning System Network (FEWS-NET), national and local extreme weather, species extinction, community-based flood and landslide, and informal pastoral drought early warning systems (Kanta Kafle 2017). Medium-term warning systems can identify areas of concern, hotspots of vulnerabilities and sensitivities, or critical zones of land degradation (areas of concern) (see Chapter 6) critical to reduce risks over five to 10 years (Selvaraju 2012). Early warning systems for dangerous climate shifts are emerging, with considerations of rate of onset, intensity, spatial distribution and predictability. Growing research in the area is considering positive and negative lessons learned from existing hazard early warning systems, including lead time and warning response (Travis 2013).

For effectiveness, communication methods are best adapted to local circumstances, religious and cultural-based structures and norms, information technology, and local institutional capacity (Cools et al. 2016; Seng 2013). Considerations of governance or the actors and architecture within the socio-ecological system, is an important feature of successful early warning system development (Seng 2013). Effective early warning systems consider the critical links between hazard monitoring, risk assessment, forecasting tools, warning and dissemination (Garcia and Fearnley 2012). These effective systems incorporate local context by defining accountability, responsibility, acknowledging the importance of risk perceptions and trust for an effective response to warnings. Although increasing levels and standardisation nationally and globally is important, revising these systems through participatory approaches cognisant of the tension with technocratic approaches improves success (Cools et al. 2016; Henriksen et al. 2018; Garcia and Fearnley 2012).

7.4.3.2 Drought-related risk minimising instruments

A more detailed review of drought instruments, and three broad policy approaches for responding to drought, is provided in Cross-Chapter Box 5 in Chapter 3. Three broad approaches include: (i) early warning systems and response to the disaster of drought (through instruments such as disaster assistance or crop insurance); (ii) disaster response ex-ante preparation (through drought preparedness plans); and (iii) drought risk mitigation (proactive polices to improve water-use efficiency, make adjustments to water allocation, funds or loans to build technology such as dugouts or improved soil management practices).

Drought plans are still predominantly reactive crisis management plans rather than proactive risk management and reduction plans. Reactive crisis management plans treat only the symptoms and are inefficient drought management practices. More efficient drought preparedness instruments are those that address the underlying vulnerability associated with the impacts of drought, thereby building agricultural producer adaptive capacity and resilience (*high confidence*) (Cross-Chapter Box 5 in Chapter 3).

7.4.3.3 Fire-related risk minimising instruments

There is *robust evidence* and *high agreement* that fire strategies need to be tailored to site-specific conditions in an adaptive application that is assessed and reassessed over time (Dellasala et al. 2004; Rocca et al. 2014). Strategies for fire management include fire suppression, prescribed fire and mechanical treatments (such as thinning the canopy), and allowing wildfire with little or no active management (Rocca et al. 2014). Fire suppression can degrade the effectiveness of forest fire management in the long run (Collins et al. 2013).

Different forest types have different fire regimes and require different fire management policies (Dellasala et al. 2004). For instance, Cerrado, a fire dependent savannah, utilises a different fire management policy and fire suppression policy (Durigan and Ratter 2016). The choice of strategy depends on local considerations, including land ownership patterns, dynamics of local meteorology, budgets, logistics, federal and local policies, tolerance for risk and landscape contexts. In addition, there are trade-offs among the management alternatives and often no single management strategy will simultaneously optimise ES, including water quality and quantity, carbon sequestration, or run-off erosion prevention (Rocca et al. 2014).

7.4.3.4 Flood-related risk minimising instruments

Flood risk management consists of command and control measures, including spatial planning and engineered flood defences (Filatova 2014), financial incentive instruments issued by regional or national governments to facilitate cooperative approaches through local planning, enhancing community understanding and political support for safe development patterns and building standards, and regulations requiring local government participation and support for local flood planning (Burby and May 2009). However, Filatova (2014) found that if autonomous adaptation is downplayed, people are more likely to make land-use choices that collectively lead to increased flood risks and leave costs to governments. Taxes and subsidies that do not encourage (and even counter) perverse behaviour (such as rebuilding in flood zones) are important instruments mitigating this cost to government. Flood insurance has been found to be maladaptive as it encourages rebuilding in flood zones (O'Hare et al. 2016) and government flood disaster assistance negatively impacts on average insurance coverage the following year (Kousky et al. 2018a). Modifications to flood insurance can counter perverse behaviour. One example is the provision of discounts on flood insurance for localities that undertake one of 18 flood mitigation activities, including structural mitigation (constructing dykes, dams, flood control reservoirs), and non-structural initiatives such as point source control and watershed management efforts, education and maintenance of flood-related databases (Zahran et al. 2010). Flood insurance that provides incentives for flood mitigation, marketable permits and transferable development rights (see Case study: Flood and food security in Section 7.6) instruments can provide price signals to stimulate autonomous adaptation, countering barriers of path dependency, and the time lag between private investment decisions and consequences (Filatova 2014). To build adaptive capacity, consideration needs to be made of policy instruments responding to flood, including flood zone mapping, land-use planning, flood zone building restrictions, business and crop insurance, disaster assistance payments, preventative instruments, (including environmental farm planning, e.g., soil and water management (see Chapter 6)), farm infrastructure projects, and recovery from debilitating flood losses ultimately through bankruptcy (Hurlbert 2018a). Non-structural measures have been found to advance sustainable development as they are more reversible, commonly acceptable and environmentally friendly (Kundzewicz 2002).

7.4.4 Policies responding to greenhouse gas (GHG) fluxes

7.4.4.1 GHG fluxes and climate change mitigation

Pathways reflecting current nationally stated mitigation ambitions as submitted under the Paris Agreement would not limit global warming to 1.5°C with no or limited overshoot, but instead result in a global warming of about 3°C by 2100 with warming continuing afterward (IPCC 2018d). Reversing warming after an overshoot of 0.2°C or higher during this century would require deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (IPCC 2018d). This gap (Höhne et al. 2017; Rogelj et al. 2016) creates a significant risk of global warming impacting on land degradation, desertification, and food security (IPCC 2018d) (Section 7.2). Action can be taken by 2030 adopting already known cost-effective technology (United Nations Environment Programme 2017), improving the finance, capacity building, and technology transfer mechanisms of the United Nations Framework Convention on Climate Change (UNFCCC), improving food security (listed by 73 nations in their nationally determined contributions (NDCs)) and nutritional security (listed by 25 nations) (Richards et al. 2015). UNFCCC Decision 1. CP21 reaffirmed the UNFCCC target that 'developed country parties provide USD 100 billion annually by 2020 for climate action in developing countries' (Rajamani 2011) and a new collective quantified goal above this floor is to be set, taking into account the needs and priorities of developing countries (Fridahl and Linnér 2016).

Mitigation policy instruments to address this shortfall include financing mechanisms, carbon pricing, cap and trade or emissions trading, and technology transfer. While climate change is a global commons problem containing free-riding issues cost-effective international policies that ensure that countries get the most environmental benefit out of mitigation investments promote an international climate policy regime (Nordhaus 1999; Aldy and Stavins 2012). Carbon pricing instruments may provide an entry point for inclusion of appropriate agricultural carbon instruments. Models of cost-efficient distribution of mitigation across regions and sectors typically employ a global uniform carbon price, but such treatment in the agricultural sector may impact on food security (Section 7.4.4.4).

One policy initiative to advance climate mitigation policy coherence in this section is the phase out of subsidies for fossil fuel production (see also Section 7.4.8). The G20 agreed in 2009, and the G7 agreed in 2016, to phase out these subsidies by 2025. Subsidies include lower tax rates or exemptions and rebates of taxes on fuels used by particular consumers (diesel fuel used by farming, fishing, etc.), types of fuel, or how fuels are used. The OECD estimates the overall value of these subsides to be 160–200 billion USD annually between 2010 and 2014 (OECD 2015). The phase-out of fossil fuel subsidies has important economic, environmental and social benefits. Coady et al. (2017) estimate the economic and environmental benefits of reforming fossil fuel subsidies could be valued worldwide at 4.9 trillion USD in 2013, and 5.3 trillion USD in 2015. Eliminating subsidies could have reduced emissions by 21%, raised 4% of global GDP as revenue (in 2013), and improved social welfare (Coady et al. 2017).

Legal instruments addressing perceived deficiencies in climate change mitigation include human rights and liability. Developments in attribution science are improving the ability to detect human influence on extreme weather. Marjanac et al. (2017) argue that this broadens the legal duty of government, business and others to manage foreseeable harms, and may lead to more climate change litigation (Marjanac et al. 2017). Peel and Osofsky (2017) argue that courts are becoming increasingly receptive to employ human rights claims in climate change lawsuits (Peel and Osofsky 2017); citizen suits in domestic courts are not a universal phenomenon and, even if unsuccessful, Estrin (2016) concludes they are important in underlining the high level of public concern.

7.4.4.2 Mitigation instruments

Similar instruments for mitigation could be applied to the land sector as in other sectors, including: market-based measures such as taxes and cap and trade systems; standards and regulations; subsidies and tax credits; information instruments and management tools; R&D investment; and voluntary compliance programmes. However, few regions have implemented agricultural mitigation instruments

(Cooper et al. 2013). Existing regimes focus on subsidies, grants and incentives, and voluntary offset programmes.

7.4.4.3 Market-based instruments

Although carbon pricing is recognised to be an important cost-effective instrument in a portfolio of climate policies (*high evidence*, *high agreement*) (Aldy et al. 2010), as yet, no country is exposing their agricultural sector emissions to carbon pricing in any comprehensive way. A carbon tax, fuel tax, and carbon markets (cap and trade system or Emissions Trading System (ETS), or baseline and credit schemes, and voluntary markets) are predominant policy instruments that implement carbon pricing. The advantage of carbon pricing is environmental effectiveness at relatively low cost (*high evidence*, *high agreement*) (Baranzini et al. 2017; Fawcett et al. 2014). Furthermore, carbon pricing could be used to raise revenue to reinvest in public spending, either to help certain sectors transition to lower carbon systems, or to invest in public spending unrelated to climate change. Both of these options may make climate policies more attractive and enhance overall welfare (Siegmeier et al. 2018), but there is, as yet, no evidence of the effectiveness of emissions pricing in agriculture (Grosjean et al. 2018). There is, however, a clear need for progress in this area as, without effective carbon pricing, the mitigation potential identified in chapters 5 and 6 of this report will not be realised (*high evidence*, *high agreement*) (Boyce 2018).

The price may be set at the social cost of carbon (the incremental impact of emitting an additional tonne of CO_2, or the benefit of slightly reducing emissions), but estimates of the SCC vary widely and are contested (*high evidence*, *high agreement*) (Pezzey 2019). An alternative to the SCC includes a pathways approach that sets an emissions target and estimates the carbon prices required to achieve this at the lowest possible cost (Pezzey 2019). Theoretically, higher costs throughout the entire economy result in reduction of carbon intensity, as consumers and producers adjust their decisions in relation to prices corrected to reflect the climate externality (Baranzini et al. 2017).

Both carbon taxes and cap and trade systems can reduce emissions, but cap and trade systems are generally more cost effective (*medium evidence*, *high agreement*) (Haites 2018a). In both cases, the design of the system is critical to its effectiveness at reducing emissions (*high evidence*, *high agreement*) (Bruvoll and Larsen 2004; (Lin and Li 2011). The trading system allows the achievement of emission reductions in the most cost-effective manner possible and results in a market and price on emissions that create incentives for the reduction of carbon pollution. The way allowances are allocated in a cap and trade system is critical to its effectiveness and equity. Free allocations can be provided to trade-exposed sectors, such as agriculture, either through historic or output-based allocations, the choice of which has important implications (Quirion 2009). Output-based allocations may be most suitable for agriculture, also minimising leakage risk (see below in this section) (Grosjean et al. 2018; Quirion 2009). There is *medium evidence* and *high agreement* that properly designed, a cap and trade system can be a powerful policy instrument (Wagner 2013) and may collect more rents than a variable carbon tax (Siegmeier et al. 2018; Schmalensee and Stavins 2017).

In the land sector, carbon markets are challenging to implement. Although several countries and regions have an ETS in place (for example, the EU, Switzerland, the Republic of Korea, Quebec in Canada, California in the USA (Narassimhan et al. 2018)), none have included non-CO_2 (methane and nitrous oxide) emissions from agriculture. New Zealand is the only country currently considering ways to incorporate agriculture into its ETS (see Case study: Including agriculture in the New Zealand Emissions Trading Scheme).

Three main reasons explain the lack of implementation to date:

1. The large number of heterogeneous buyers and sellers, combined with the difficulties of monitoring, reporting and verification (MRV) of emissions from biological systems introduce potentially high levels of complexity (and transaction costs). Effective policies therefore depend on advanced MRV systems which are lacking in many (particularly developing) countries (Wilkes et al. 2017). This is discussed in more detail in the case study on the New Zealand Emissions Trading Scheme.
2. Adverse distributional consequences (Grosjean et al. 2018) (*medium evidence*, *high agreement*). Distributional issues depend, in part, on the extent that policy costs can be passed on to consumers, and there is *medium evidence* and *medium agreement* that social equity can be increased through a combination of non-market and market-based instruments (Haites 2018b).
3. Regulation, market-based or otherwise, adopted in only one jurisdiction and not elsewhere may result in 'leakage' or reduced effectiveness – where production relocates to weaker regulated regions, potentially reducing the overall environmental benefit. Although modelling studies indicate the possibility of leakage following unilateral agricultural mitigation policy implementation (e.g., Fellmann et al. 2018), there is no empirical evidence from the agricultural sector yet available. Analysis from other sectors shows an overestimation of the extent of carbon leakage in modelling studies conducted before policy implementation compared to evidence after the policy was implemented (Branger and Quirion 2014). Options to avoid leakage include: border adjustments (emissions in non-regulated imports are taxed at the border, and payments made on products exported to non-regulated countries are rebated); differential pricing for trade-exposed products; and output-based allocation (which effectively works as a subsidy for trade-exposed products). Modelling shows that border adjustments are the most effective at reducing leakage, but may exacerbate regional inequality (Böhringer et al. 2012) and through their trade-distorting nature may contravene World Trade Organization rules. The opportunity for leakage would be significantly reduced, ideally through multi-lateral commitments (Fellmann et al. 2018) (*medium evidence*, *high agreement*) but could also be reduced through regional or bi-lateral commitments within trade agreements.

Case study | Including agriculture in the New Zealand Emissions Trading Scheme (ETS)

New Zealand has a high proportion of agricultural emissions at 49% (Ministry of the Environment 2018) – the next-highest developed country agricultural emitter is Ireland at around 32% (EPA 2018) – and is considering incorporating agricultural non-CO_2 gases into the existing national ETS. In the original design of the ETS in 2008, agriculture was intended to be included from 2013, but successive governments deferred the inclusion (Kerr and Sweet 2008) due to concerns about competitiveness, lack of mitigation options and the level of opposition from those potentially affected (Cooper and Rosin 2014). Now though, as the country's agricultural emissions are 12% above 1990 levels, and the country's total gross emissions have increased 19.6% above 1990 levels (New Zealand Ministry for the Environment 2018), there is a recognition that, without any targeted policy for agriculture, only 52% of the country's emissions face any substantive incentive to mitigate (Narassimhan et al. 2018). Including agriculture in the ETS is one option to provide incentives for emissions reductions in that sector. Other options are discussed in Section 7.4.4. Although some producer groups raise concern that including agriculture will place New Zealand producers at a disadvantage compared with their international competitors who do not face similar mechanisms (New Zealand Productivity Commission 2018), there is generally greater acceptance of the need for climate policies for agriculture.

The inclusion of non-CO_2 emissions from agriculture within an ETS is potentially complex, however, due to the large number of buyers and sellers if obligations are placed at farm level, and different choices of how to estimate emissions from biological systems in cost-effective ways. New Zealand is currently investigating practical and equitable approaches to include agriculture through advice being provided by the Interim Climate Change Committee (ICCC 2018). Main questions centre around the point of obligation for buying and selling credits, where trade-offs have to be made between providing incentives for behaviour change at farm level and the cost and complexity of administering the scheme (Agriculture Technical Advisory Group 2009; Kerr and Sweet 2008). The two potential points of obligation are at the processor level or at the individual farm level. Setting the point of obligation at the processor level means that farmers would face limited incentive to change their management practices, unless the processors themselves rewarded farmers for lowered emissions. Setting it at the individual farm level would provide a direct incentive for farmers to adopt mitigation practices, however, the reality of having thousands of individual points of obligation would be administratively complex and could result in high transaction costs (Beca Ltd 2018).

Monitoring, reporting and verification (MRV) of agricultural emissions presents another challenge, especially if emissions have to be estimated at farm level. Again, trade-offs have to be made between accuracy and detail of estimation method and the complexity, cost and audit of verification (Agriculture Technical Advisory Group 2009).

The ICCC is also exploring alternatives to an ETS to provide efficient abatement incentives (ICCC 2018).

Some discussion in New Zealand also focuses on a differential treatment of methane compared to nitrous oxide. Methane is a short-lived gas with a perturbation lifetime of 12 years in the atmosphere; nitrous oxide on the other hand is a long-lived gas and remains in the atmosphere for 114 years (Allen et al. 2016). Long-lived gases have a cumulative and essentially irreversible effect on the climate (IPCC 2014b) so their emissions need to reduce to net-zero in order to avoid climate change. Short-lived gases, however, could potentially be reduced to a certain level and then stabilised, and would not contribute further to warming, leading to suggestions of treating these two gases separately in the ETS or alternative policy instruments, possibly setting different budgets and targets for each (New Zealand Productivity Commission 2018). Reisinger et al. (2013) demonstrate that different metrics can have important implications globally and potentially at national and regional scales on the costs and levels of abatement.

While the details are still being agreed on in New Zealand, almost 80% of nationally determined contributions committed to action on mitigation in agriculture (FAO 2016), so countries will be looking for successful examples.

Australia's Emissions Reduction Fund, and the preceding Carbon Farming Initiative, are examples of baseline-and-credit schemes, which set an emissions intensity baseline and create credits for activities that generate emissions below the baseline – effectively a subsidy (Freebairn 2016). It is a voluntary scheme, and has the potential to create real and additional emission reductions through projects reducing emissions and sequestering carbon (Verschuuren 2017) (*low evidence*, *low agreement*). Key success factors in the design of such an instrument are policy-certainty for at least 10 to 20years, regulation that focuses on projects and not uniform rules, automated systems for all phases of the projects, and a wider focus of the carbon farming initiative on adaptation, food security, sustainable farm business, and creating jobs (Verschuuren 2017). A recent review highlighted the issue of permanence and reversal, and recommended that projects detail how they will maintain carbon in their projects, and deal with the risk of fire.

7.4.4.4 Technology transfer and land-use sectors

Technology transfer has been part of the UNFCCC process since its inception and is a key element of international climate mitigation and adaptation efforts under the Paris Agreement. The IPCC definition of 'technology transfer' includes transfer of knowledge and technological cooperation (see Glossary) and can include modifications to suit local conditions and/or integration with indigenous technologies (Metz et al. 2000). This definition suggests greater heterogeneity in the applications for climate mitigation and adaptation, especially in land-use sectors where indigenous knowledge may be important for long-term climate resilience (Nyong et al. 2007). For land-use sectors, the typical reliance on trade and patent data for empirical analyses is generally not feasible as the 'technology' in question is often related to resource management and is neither patentable nor tradable (Glachant and Dechezleprêtre 2017) and ill-suited to provide socially beneficially innovation for poorer farmers in developing countries (Lybbert and Sumner 2012; Baker et al. 2017).

Technology transfer has contributed to emissions reductions (*medium confidence*). A detailed study for nearly 4000 Clean Development Mechanism (CDM) projects showed that 39% of projects had a stated and actual technology transfer component, accounting for 59% of emissions reductions; however, the more land-intensive projects (e.g., afforestation, bioenergy) showed lower percentages (Murphy et al. 2015). Bioenergy projects that rely on agricultural residues offer substantially more development benefits than those based on industrial residues from forests (Lee and Lazarus 2013). Energy projects tended to have a greater degree of technology transfer under the CDM compared to non-energy projects (Gandenberger et al. 2016). However, longer-term cooperation and collaborative R&D approaches to technology transfer will be more important in land-use sectors (compared to energy or industry) due to the time needed for improved resource management and interaction between researchers, practitioners and policymakers. These approaches offer longer-term technology transfer that is more difficult to measure compared to specific cooperation projects; empirical research on the effects of R&D collaboration could help to avoid the 'one-policy-fits-all' approach (Ockwell et al. 2015).

There is increasing recognition of the role of technology transfer in climate adaptation, but in the land-use sector there are inherent adoption challenges specific to adaptation, due to uncertainties arising from changing climatic conditions, agricultural prices, and suitability under future conditions (Biagini et al. 2014). Engaging the private sector is important, as adoption of new technologies can only be replicated with significant private sector involvement (Biagini and Miller 2013).

7.4.4.5 International cooperation under the Paris Agreement

New cooperative mechanisms under the Paris Agreement illustrate the shift away from the Kyoto Protocol's emphasis on obligations of developed country Parties to pursue investments and technology transfer, to a more pragmatic, decentralised and collaborative approach (Savaresi 2016; Jiang et al. 2017). These approaches can effectively include any combination of measures or instruments related to adaptation, mitigation, finance, technology transfer and capacity building, which could be of particular interest in land-use sectors where such aspects are more intertwined than in energy or industry sectors. Article 6 sets out several options for international cooperation (Gupta and Dube 2018).

The close relationship between emission reductions, adaptive capacity, food security and other sustainability and governance objectives in the land sectors means that Article 6 could bring co-benefits that increase its attractiveness and the availability of finance, while also bringing risks that need to be monitored and mitigated against, such as uncertainties in measurements and the risk of non-permanence (Thamo and Pannell 2016; Olsson et al. 2016; Schwartz et al. 2017). There has been progress in accounting for land-based emissions, mainly forestry and agriculture (*medium evidence*, *low agreement*), but various challenges remain (Macintosh 2012; Pistorius et al. 2017; Krug 2018).

Like the CDM and other existing carbon trading mechanisms, participation in Article 6.2 and 6.4 of the Paris Agreement requires certain institutional and data management capacities in the land sector to effectively benefit from the cooperation opportunities (Totin et al. 2018). While the rules for the implementation of the new mechanisms are still under development, lessons from REDD+ (reducing emissions from deforestation and forest degradation) may be useful, which is perceived as more democratic and participative than the CDM (Maraseni and Cadman 2015). Experience with REDD+ programmes emphasise the necessity to invest in 'readiness' programmes that assist countries to engage in strategic planning and build management and data collection systems to develop the capacity and infrastructure to participate in REDD+ (Minang et al. 2014). The overwhelming majority of countries (93%) cite weak forest sector governance and institutions in their applications for REDD+ readiness funding (Kissinger et al. 2012). Technology transfer for advanced remote sensing technologies that help to reduce uncertainty in monitoring forests helps to achieve REDD+ 'readiness' (Goetz et al. 2015).

As well as new opportunities for finance and support, the Paris cooperation mechanisms and the associated roles for technology transfer bring new challenges, particularly in reporting, verifying and accounting in land-use sectors. Since developing countries must now achieve, measure and communicate emission reductions, they now have value for both developing and developed countries in achieving their NDCs, but reductions cannot be double-counted (i.e., towards multiple NDCs). All countries have to prepare and communicate NDCs, and many countries have included in their NDCs either economy-wide targets that include the land-use sectors, or specific targets for the land-use sectors. The Katowice climate package clarifies that all Parties have to submit 'Biennial Transparency Reports' from 2024 onwards, using common reporting formats, following most recent IPCC Guidelines (use of the 2013 Supplement on Wetlands is encouraged), identifying key categories of emissions, ensuring time-series consistency, and providing completeness and uncertainty assessments as well as quality control (UNFCCC 2018a; Schneider and La Hoz Theuer 2019). In total, the ambiguity in how countries incorporate land-use sectors into their NDC is estimated to lead to an uncertainty of more than 2 $GtCO_2$ in 2030 (Fyson and Jeffery 2018). Uncertainty is lower if the analysis is limited to countries that have provided separate land-use sector targets in their NDCs (Benveniste et al. 2018).

7.4.5 Policies responding to desertification and degradation – Land Degradation Neutrality (LDN)

Land Degradation Neutrality (LDN) (SDG Target 15.3), evolved from the concept of Net Zero Land Degradation, which was introduced by the United Nations Convention to Combat Desertification (UNCCD) to promote SLM (Kust et al. 2017; Stavi and Lal 2015; Chasek et al. 2015). Neutrality here implies no net loss of the land-based natural resource and ES relative to a baseline or a reference state (UNCCD 2015; Kust et al. 2017; Easdale 2016; Cowie et al. 2018a; Stavi and Lal 2015; Grainger 2015; Chasek et al. 2015). LDN can be achieved by reducing the rate of land degradation (and concomitant loss of ES) and increasing the rate of restoration and rehabilitation of degraded or desertified land. Therefore, the rate of global land degradation is not to exceed that of land restoration in order to achieve LDN goals (adopted as national platform for actions by more than 100 countries) (Stavi and Lal 2015; Grainger 2015; Chasek et al. 2015; Cowie et al. 2018a; Montanarella 2015). Achieving LDN would decrease the environmental footprint of agriculture, while supporting food security and sustaining human well-being (UNCCD 2015; Safriel 2017; Stavi and Lal 2015; Kust et al. 2017).

Response hierarchy – avoiding, reducing and reversing land degradation – is the main policy response (Chasek et al. 2019, Wonder and Bodle 2019, Cowie et al. 2018, Orr et al. 2017). The LDN response hierarchy encourages through regulation, planning and management instruments, the adoption of diverse measures to avoid, reduce and reverse land degradation in order to achieve LDN (Cowie et al. 2018b; Orr et al. 2017).

Chapter 3 categorised policy responses into two categories; (i) avoiding, reducing and reversing it through SLM; and (ii) providing alternative livelihoods with economic diversification. LDN could be achieved through planned effective actions, particularly by motivated stakeholders – those who play an essential role in a land-based climate change adaptation (Easdale 2016; Qasim et al. 2011; Cowie et al. 2018a; Salvati and Carlucci 2014). Human activities impacting the sustainability of drylands is a key consideration in adequately reversing degradation through restoration or rehabilitation of degraded land (Easdale 2016; Qasim et al. 2011; Cowie et al. 2018a; Salvati and Carlucci 2014).

LDN actions and activities play an essential role for a land-based approach to climate change adaptation (UNCCD 2015). Policies responding to degradation and desertification include improving market access, gender empowerment, expanding access to rural advisory services, strengthening land tenure security, payments for ES, decentralised natural resource management, investing in R&D, modern renewable energy sources and monitoring of desertification and desert storms, developing modern renewable energy sources, and developing and strengthening climate services. Policy supporting economic diversification includes investing in irrigation, expanding agricultural commercialisation, and facilitating structural transformations in rural economies (Chapter 3). Policies and actions also include promoting indigenous and local knowledge (ILK), soil conservation, agroforestry, crop-livestock interactions as an approach to manage land degradation, and forest-based activities such as afforestation, reforestation, and changing forest

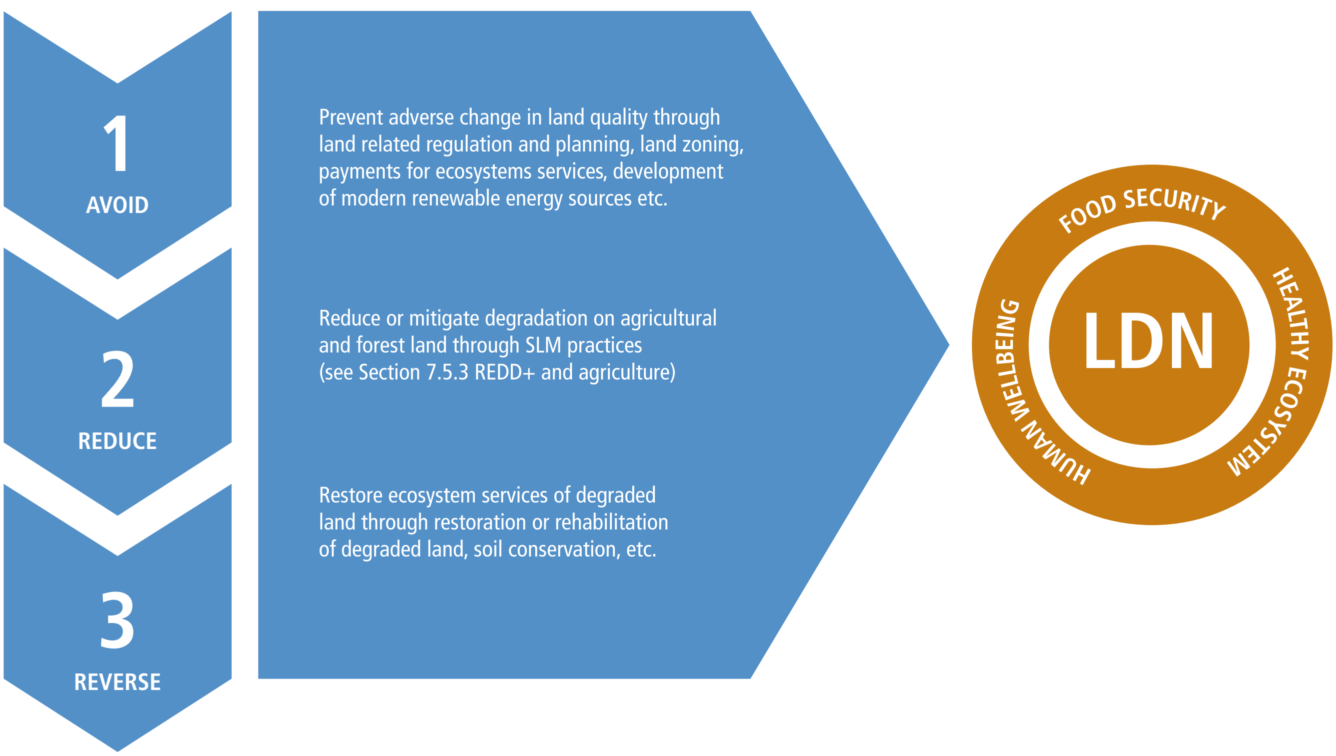

Figure 7.4 | LDN response hierarchy. Source: Adapted from (Liniger et al. 2019; UNCCD/Science-Policy-Interface 2016).

management (Chapter 4). Measures identified for achievement of LDN include effective financial mechanisms (for implementation of land restoration measures and the long-term monitoring of progress), parameters for assessing land degradation, detailed plans with quantified objectives and timelines (Kust et al. 2017; Sietz et al. 2017; Cowie et al. 2018a; Montanarella 2015; Stavi and Lal 2015).

Implementing the international LDN target into national policies has been a challenge (Cowie et al. 2018a; Grainger 2015) as baseline land degradation or desertification information is not always available (Grainger 2015) and challenges exist in monitoring LDN as it is a dynamic process (Sietz et al. 2017; Grainger 2015; Cowie et al. 2018a). Wunder and Bodle (2019) propose that LDN be implemented and monitored through indicators at the national level. Effective implementation of global LDN will be supported by integrating lessons learned from existing programmes designed for other environmental objectives and closely coordinate LDN activities with actions for climate change adaptation and mitigation at both global and national levels (*high confidence*) (Stavi and Lal 2015; Grainger 2015).

7.4.6 Policies responding to land degradation

7.4.6.1 Land-use zoning

Land-use zoning divides a territory (including local, sub-regional or national) into zones with different rules and regulations for land use (mining, agriculture, urban development, etc.), management practices and land-cover change (Metternicht 2018). While the policy instrument is zoning ordinances, the process of determining these regulations is covered in integrated land-use planning (Section 7.6.2). Urban zoning can guide new growth in urban communities outside forecasted hazard areas, assist relocating existing dwellings to safer sites and manage post-event redevelopment in ways to reduce future vulnerability (Berke and Stevens 2016). Holistic integration of climate mitigation and adaptation are interdependent and can be implemented by restoring urban forests, and improving parks (Brown 2010; Berke and Stevens 2016). Zoning ordinances can contribute to SLM through protection of natural capital by preventing or limiting vegetation clearing, avoiding degradation of planning for rehabilitation of degraded land or contaminated sites, promoting conservation and enhancement of ecosystems and ecological corridors (Metternicht 2018; Jepson and Haines 2014). Zoning ordinances can also encourage higher density development, mixed use, local food production, encourage transportation alternatives (bike paths and transit-oriented development), preserve a sense of place, and increase housing diversity and affordability (Jepson and Haines 2014). Conservation planning varies by context and may include one or several adaptation approaches, including protecting current patterns of biodiversity, large intact natural landscapes, and geophysical settings. Conservation planning may also maintain and restore ecological connectivity, identify and manage areas that provide future climate space for species expected to be displaced by climate change, and identify and protect climate refugia (Stevanovic et al. 2016; Schmitz et al. 2015).

Anguelovski et al. (2016) studied land-use interventions in eight cities in the global north and south, and concluded that historic trends of socio-economic vulnerability can be reinforced. They also found that vulnerability could be avoided with a consideration of the distribution of adaptation benefits and prioritising beneficial outcomes for disadvantaged and vulnerable groups when making future adaptation plans. Concentration of adaptation resources within wealthy business districts creating ecological enclaves exacerbated climate risks elsewhere and building of climate adaptive infrastructure such as sea walls or temporary flood barriers occurred at the expense of underserved neighbourhoods (Anguelovski et al. 2016a).

7.4.6.2 Conserving biodiversity and ecosystem services (ES)

There is *limited evidence* but *high agreement* that ecosystem-based adaptation (biodiversity, ecosystem services (ES), and Nature's Contribution to People (see Chapter 6)) and incentives for ES – including payment for ecosystem services (PES) – play a critical part of an overall strategy to help people adapt to the adverse effects of climate change on land (UNEP 2009; Bonan 2008; Millar et al. 2007; Thompson et al. 2009).

Ecosystem-based adaptation can promote socio-ecological resilience by enabling people to adapt to the impacts of climate change on land and reduce their vulnerability (Ojea 2015). Ecosystem-based adaptation can promote nature conservation while alleviating poverty and even provide co-benefits by removing GHGs (Scarano 2017) and protecting livelihoods (Munang et al. 2013). For example, mangroves provide diverse ES such as carbon storage, fisheries, non-timber forest products, erosion protection, water purification, shore-line stabilisation, and also regulate storm surge and flooding damages, thus enhancing resilience and reducing climate risk from extreme events such as cyclones (Rahman et al. 2014; Donato et al. 2011; Das and Vincent 2009; Ghosh et al. 2015; Ewel et al. 1998).

There has been considerable increase in the last decade of PES, or programmes that exchange value for land management practices intended to ensure ES (Salzman et al. 2018; Yang and Lu 2018; Barbier 2011). However, there is a deficiency in comprehensive and reliable data concerning the impact of PES on ecosystems, human well-being, their efficiency, and effectiveness (Pynegar et al. 2018; Reed et al. 2014; Salzman et al. 2018; Barbier 2011; Yang and Lu 2018). While some studies assess ecological effectiveness and social equity, fewer assess economic efficiency (Yang and Lu 2018). Part of the challenge surrounds the fact that the majority of ES are not marketed, so determining how changes in ecosystems structures, functions and processes influence the quantity and quality of ES flows to people is challenging (Barbier 2011). PES include agri-environmental targeted outcome-based payments, but challenges exist in relation to scientific uncertainty, pricing, timing of payments, increasing risk to land managers, World Trade Organization compliance, and barriers of land management and scale (Reed et al. 2014).

PES is contested (Wang and Fu 2013; Czembrowski and Kronenberg 2016; Perry 2015) for four reasons: (i) understanding and resolving trade-offs between conflicting groups of stakeholders (Wam et al.

2016; Matthies et al. 2015); (ii) knowledge and technology capacity (Menz et al. 2013); (iii) challenges integrating PES with economic and other policy instruments (Ring and Schröter-Schlaack 2011; Tallis et al. 2008; Elmqvist et al. 2003; Albert et al. 2014); and (iv) top-down climate change mitigation initiatives which are still largely carbon-centric, with limited opportunities for decentralised ecological restoration at local and regional scales (Vijge and Gupta 2014).

These challenges and contestations can be resolved with the participation of people in establishing PES, thereby addressing trust issues, negative attitudes, and resolving trade-offs between issues (such as retaining forests that consume water versus the provision of run-off, or balancing payments to providers versus cost to society) (Sorice et al. 2018; Matthies et al. 2015). Similarly, a 'co-constructive' approach is used involving a diversity of stakeholders generating policy-relevant knowledge for sustainable management of biodiversity and ES at all relevant spatial scales, by the current Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) initiative (Díaz et al. 2015). Invasive species are also best identified and managed with the participation of people through collective decisions, coordinated programmes, and extensive research and outreach to address their complex social-ecological impacts (Wittmann et al. 2016; Epanchin-Niell et al. 2010).

Ecosystem restoration with co-benefits for diverse ES can be achieved through passive restoration, passive restoration with protection, and active restoration with planting (Birch et al. 2010; Cantarello et al. 2010). Taking into account the costs of restoration and co-benefits from bundles of ES (carbon, tourism, timber), the benefit-cost ratio (BCR) of active restoration and passive restoration with protection was always less than 1, suggesting that financial incentives would be required. Passive restoration was the most cost-effective with a BCR generally between 1 and 100 for forest, grassland and shrubland restoration (TEEB 2009; Cantarello et al. 2010). Passive restoration is generally more cost-effective, but there is a danger that it could be confused with abandoned land in the absence of secure tenure and a long time period (Zahawi et al. 2014). Net social benefits of degraded land restoration in dry regions range from about 200–700 USD per hectare (Cantarello et al. 2010). Investments in active restoration could benefit from analyses of past land use, the natural resilience of the ecosystem, and the specific objectives of each project (Meli et al. 2017). One successful example is the Working for Water Programme in South Africa that linked restoration through removal of invasive species and enhanced water security (Milton et al. 2003).

Forest, water and energy cycle interactions and teleconnections such as contribution to rainfall potentially (Aragão 2012; Ellison et al. 2017; Paul et al. 2018; Spracklen et al. 2012) provide a foundation for achieving forest-based adaptation and mitigation goals. They are, however, poorly integrated in policy and decision-making, including PES (Section 2.5.4).

7.4.6.3 Standards and certification for sustainability of biomass and land-use sectors

During the past two decades, standards and certification have emerged as important sustainability and conservation instruments for agriculture, forestry, bioenergy, land-use management and bio-based products (Lambin et al. 2014; Englund and Berndes 2015; Milder et al. 2015; Giessen et al. 2016a; Endres et al. 2015; Byerlee et al. 2015; van Dam et al. 2010). Standards are normally voluntary, but can also become obligatory through legislation. A standard provides specifications or guidelines to ensure that materials, products, processes and services are fit for purpose, whereas certification is the procedure through which an accredited party confirms that a product, process or service is in conformity with certain standards. Standards and certification are normally carried out by separate organisations for legitimacy and accountability (Section 7.6.6). The International Organization for Standardization is a key source for global environmental standards. Those with special relevance for land and climate include a recent standard on combating land degradation and desertification (ISO 2017) and an earlier standard on sustainable bioenergy and biomass use (ISO 2015; Walter et al. 2018). Both aim to support the long-term transition to a climate-resilient bioeconomy; there is *medium evidence* on the sustainability implications of different bioeconomy pathways, but *low agreement* as to which pathways are socially and environmentally desirable (Priefer et al. 2017; Johnson 2017; Bennich et al. 2017a).

Table 7.3 provides a summary of selected standards and certification schemes with a focus on land use and climate: the tickmark shows inclusion of different sustainability elements, with all recognising the inherent linkages between the biophysical and social aspects of land use. Some certification schemes and best practice guidelines are specific to a particular agriculture crop (e.g., soya, sugarcane) or a tree (e.g., oil palm) while others are general. International organisations promote sustainable land and biomass use through good practice guidelines, voluntary standards and jurisdictional approaches (Scarlat and Dallemand 2011; Stattman et al. 2018a). Other frameworks, such as the Global Bioenergy Partnership (GBEP) focus on monitoring land and biomass use through a set of indicators that are applied across partner countries, thereby also promoting technology/knowledge transfer (GBEP 2017). The Economics of Land Degradation (ELD) Initiative provides common guidelines for economic assessments of land degradation (Nkonya et al. 2013).

Whereas current standards and certification focus primarily on land, climate and biomass impacts where they occur, more recent analysis considers trade-related land-use change by tracing supply chain impacts from producer to consumer, leading to the notion of 'imported deforestation' that occurs from increasing demand and trade in unsustainable forest and agriculture products, which is estimated to account for 26% of all tropical deforestation (Pendrill et al. 2019). Research and implementation efforts aim to improve supply chain transparency and promote commitments to 'zero deforestation' (Gardner et al. 2018a; Garrett et al. 2019; Newton et al. 2018; Godar and Gardner 2019; Godar et al. 2015, 2016). France has developed specific policies on imported deforestation

Table 7.3 | Selected standards and certification schemes and their components or coverage.

Acronym	Scheme, programme or standard	Commodity/process, relation to others	Type of mechanism	Environmental						Socio-economic		
				GHG emissions	Biodiversity	Carbon stock	Soil	Air	Water	Land-use management[a]	Land rights	Food security[b]
ISCC	International Sustainability and Carbon Certification	All feedstocks, all supply chains	Certification	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bonsucro	Bonsucro EU	Sugar cane and derived products	Certification	✓	✓	✓	✓	✓	✓	✓	✓	
RTRS	Roundtable on Responsible Soy EU	Soy-based products	Certification	✓	✓	✓	✓	✓	✓	✓	✓	
RSB	Roundtable on Sustainable Biomaterials EU	Biomass for biofuels and biomaterials	Certification	✓	✓	✓	✓	✓	✓	✓	✓	✓
SAN	Sustainable Agriculture	Various agricultural crops and commodities; linked to Rain Forest Alliance	Technical Network		✓	✓	✓	✓	✓	✓		
RSPO RED	Roundtable on Sustainable Palm Oil RED	Palm oil products	Certification	✓	✓	✓	✓	✓	✓	✓	✓	✓
PEFC	Programme for Endorsement of Forest Certification	Forest management	Certification		✓	✓	✓	✓	✓	✓	✓	[c]
FSC	Forest Stewardship Council	Forest management	Certification		✓	✓	✓	✓	✓	✓	✓	
SBP	Sustainable Biomass Programme	Woody biomass (e.g., wood pellets, wood chips); linked to PEFC and FSC	Certification	✓	✓	✓	✓	✓	✓	✓	✓	
WOCAT	World Overview of Conservation Approaches and Technologies	Global network on sustainable land management	Best Practice Network			✓	✓	✓	✓	✓		
ISO 13065: 2015	Bioenergy	Biomass and bioenergy, including conversion processes	Standard	✓	✓	✓	✓	✓	✓	✓	✓	✓[d]
ISO 14055–1: 2017	Land Degradation and Desertification	Land-use management, including restoration of degraded land	Standard	✓				✓	✓	✓	✓	

Source: Modified from (European Commission 2012; Diaz-Chavez 2015).

✓ indicates that the issue is addressed in the standard or scheme

[a] includes restoration of degraded land in some cases (especially ISO 14055–1)

[b] where specifically indicated

[c] reference to the RSB certification/standard

[d] where specifically noted

that are expected to eventually include a 'zero deforestation' label (Government of France 2019).

The sustainability of biofuels and bioenergy has been in particular focus during the past decade or so due to biofuel mandates and renewable energy policies in the USA, EU and elsewhere (van Dam et al. 2010; Scarlat and Dallemand 2011). The European Union Renewable Energy Directive (EU-RED) established sustainability criteria in relation to EU renewable energy targets in the transport sector (European Commission 2012), which subsequently had impacts on land use and trade with third-party countries (Johnson et al. 2012). In particular, the EU-RED marked a departure in the context of Kyoto/UNFCCC guidelines by extending responsibility for emissions beyond the borders of final use, and requiring developing countries wishing to sell into the EU market to meet the sustainability criteria (Johnson 2011b). The recently revised EU-RED provides sustainability criteria that include management of land and forestry as well as socio-economic aspects (European Union 2018; Faaij 2018; Stattman et al. 2018b). Standards and certification aim to address potential conflicts between different uses of biomass, and most schemes also consider co-benefits and synergies (see Cross-Chapter Box 7 in Chapter 6). Bioenergy may offer additional income and livelihoods to farmers as well as improvements in technical productivity and multi-functional landscapes (Rosillo Callé and Johnson 2010a; Kline et al. 2017; Araujo Enciso et al. 2016). Results depend on the commodities involved, and also differ between rural and urban areas.

Analyses on the implementation of standards and certification for land and biomass use have focused on their stringency, effectiveness and geographical scope as well as socio-economic impacts such as land tenure, gender and land rights (Diaz-Chavez 2011; German and Schoneveld 2012; Meyer and Priess 2014). The level of stringency and enforcement varies with local environmental conditions, governance approaches and the nature of the feedstock produced (Endres et al. 2015; Lambin et al. 2014; Giessen et al. 2016b; Stattman et al. 2018b). There is *low evidence* and *low agreement* on how the application and use of standards and certification has actually improved sustainability beyond the local farm, factory or plantation level; the lack of harmonisation and consistency across countries that has been observed, even within a common market or economic region such as the EU, presents a barrier to wider market impacts (Endres et al. 2015; Stattman et al. 2018b; ISEAL Alliance 2018). In the forest sector, there is evidence that certification programmes such as the Forest Stewardship Council (FSC) have reduced deforestation in the aggregate, as well as reducing air pollution (Miteva et al. 2015; Mcdermott et al. 2015). Certification and standards cannot address global systemic concerns such as impacts on food prices or other market-wide effects, but rather are aimed primarily at insuring best practices in the local context. More general approaches to certification such as the Gold Standard are designed to accelerate progress toward the SDGs as well as the Paris Climate Agreement by certifying investment projects while also emphasising support to governments (Gold Standard).

7.4.6.4 Energy access and biomass use

Access to modern energy services is a key component of SDG 7, with an estimated 1.1 billion people lacking access to electricity, while nearly 3 billion people rely on traditional biomass (fuelwood, agriculture residues, animal dung, charcoal) for household energy needs (IEA 2017). Lack of access to modern energy services is significant in the context of land-climate systems because heavy reliance on traditional biomass can contribute to land degradation, household air pollution and GHG emissions (see Cross-Chapter Box 12 in Chapter 7). A variety of policy instruments and programmes have been aimed at improving energy access and thereby reducing the heavy reliance on traditional biomass (Table 7.2); there is *high evidence* and *high agreement* that programmes and policies that reduce dependence on traditional biomass will have benefits for health and household productivity, as well as reducing land degradation (Section 4.5.4) and GHG emissions (Bailis et al. 2015; Cutz et al. 2017a; Masera et al. 2015; Goldemberg et al. 2018a; Sola et al. 2016a; Rao and Pachauri 2017; Denton et al. 2014). There can be trade-offs across different options, especially between health and climate benefits, since more efficient wood stoves might have only limited effect, whereas gaseous and liquid fuels (e.g., biogas, LPG, bioethanol) will have highly positive health benefits and climate benefits that vary depending on specific circumstances of the substitution (Cameron et al. 2016; Goldemberg et al. 2018b). Unlike traditional biomass, modern bioenergy offers high-quality energy services, although, for household cookstoves, even the cleanest options using wood may not perform as well in terms of health and/or climate benefits (Fuso Nerini et al. 2017; Goldemberg et al. 2018b).

Case study | Forest conservation instruments: REDD+ in the Amazon and India

More than 50 countries have developed national REDD+ strategies, which have key conditions for addressing deforestation and forest degradation (improved monitoring capacities, understanding of drivers, increased stakeholder involvement, and providing a platform to secure indigenous and community land rights). However, to achieve its original objectives and to be effective under current conditions, forest-based mitigation actions need to be incorporated in national development plans and official climate strategies, and mainstreamed across sectors and levels of government (Angelsen et al. 2018a).

The Amazon region can illustrate the complexity of the implementation of REDD+, in the most biodiverse place on the planet, with millions of inhabitants and hundreds of ethnic groups, under the jurisdiction of eight countries. While different experiences can be drawn at different spatial scales, at the regional-level, for example, Amazon Fund (van der Hoff et al. 2018), at the subnational level (Furtado 2018), and at the local level (Alvarez et al. 2016; Simonet et al. 2019), there is *medium evidence* and high agreement that

Case Study (continued)

REDD+ has stimulated sustainable land-use investments but is also competing with other land uses (e.g., agroindustry) and scarce international funding (both public and private) (Bastos Lima et al. 2017b; Angelsen et al. 2018b).

In the Amazon, at the local level, a critical issue has been the incorporation of indigenous people in the planning and distribution of benefits of REDD+ projects. While REDD+, in some cases, has enhanced participation of community members in the policy-planning process, fund management, and carbon baseline establishment, increasing project reliability and equity (West 2016), it is clear that, in this region, insecure and overlapping land rights, as well as unclear and contradictory institutional responsibilities, are probably the major problems for REDD+ implementation (Loaiza et al. 2017). Despite legal and rhetoric recognition of indigenous land rights, effective recognition is still lacking (Aguilar-Støen 2017). The key to the success of REDD+ in the Amazon, has been the application of both incentives and disincentives on key safeguard indicators, including land security, participation, and well-being (Duchelle et al. 2017).

On the other hand, at the subnational level, REDD+ has been unable to shape land-use dynamics or landscape governance, in areas suffering strong exogenous factors, such as extractive industries, and in the absence of effective regional regulation for sustainable land use (Rodriguez-Ward et al. 2018; Bastos Lima et al. 2017b). Moreover, projects with weak financial incentives, engage households with high off-farm income, which are already better off than the poorest families (Loaiza et al. 2015). Beyond operational issues, clashing interpretations of results might create conflict between implementing countries or organisations and donor countries, which have revealed concerns over the performance of projects (van der Hoff et al. 2018) REDD+ Amazonian projects often face methodological issues, including how to assess the opportunity cost among landholders, and informing REDD+ implementation (Kweka et al. 2016). REDD+ based projects depend on consistent environmental monitoring methodologies for measuring, reporting and verification and, in the Amazon, land-cover estimates are crucial for environmental monitoring efforts (Chávez Michaelsen et al. 2017).

In India, forests and wildlife concerns are on the concurrent list of the Constitution since an amendment in 1976, thus giving the central or federal government a strong role in matters related to governance of forests. High rates of deforestation due to development projects led to the Forest (Conservation) Act (1980) which requires central government approval for diversion of forest land in any state or union territory.

Before 2006, forest diversion for development projects leading to deforestation needed clearance from the Central Government under the provisions of the Forest (Conservation Act) 1980. In order to regulate forest diversion, and as payment for ES, a net present value (NPV) frame-work was introduced by the Supreme Court of India, informed by the Kanchan Chopra committee (Chopra 2017). The Forest (Conservation) Act of 1980 requires compensatory afforestation in lieu of forest diversion, and the Supreme Court established the Compensatory Afforestation Fund Management and Planning Authority (CAMPA) which collects funds for compensatory afforestation and on account of NPV from project developers.

As of February 2018, 6825 million USD had accumulated in CAMPA funds in lieu of NPV paid by developers diverting forest land throughout India for non-forest use. Funds are released by the central government to state governments for afforestation and conservation-related activities to 'compensate' for diversion of forests. This is now governed by legislation called the CAMPA Act, passed by the Parliament of India in July 2016. The CAMPA mechanism has, however, invited criticism on various counts in terms of undervaluation of forest, inequality, lack of participation and environmental justice (Temper and Martinez-Alier 2013).

The other significant development related to forest land was the landmark legislation called the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 or Forest Rights Act (FRA) passed by the Parliament of India in 2007. This is the largest forest tenure legal instrument in the world and attempted to undo historical injustice to forest dwellers and forest-dependent communities whose traditional rights and access were legally denied under forest and wildlife conservation laws. The FRA recognises the right to individual land titles on land already cleared, as well as community forest rights such as collection of forest produce. A total of 64,328 community forest rights and a total of 17,040,343 individual land titles had been approved and granted up to the end of 2017. Current concerns on policy and implementation gaps are about strengths and pitfalls of decentralisation, identifying genuine right holders, verification of land rights using technology and best practices, and curbing illegal claims (Sarap et al. 2013; Reddy et al. 2011; Aggarwal 2011; Ramnath 2008; Ministry of Environment and Forests and Ministry and Tribal Affairs, Government of India 2010).

Case Study (continued)

As per the FRA, the forest rights shall be conferred free of all encumbrances and procedural requirements. Furthermore, without the FRA's provision for getting the informed consent of local communities for both diversion of community forest land and for reforestation, there would be legal and administrative hurdles in using existing forest land for implementation of India's ambitious Green India Mission that aims to respond to climate change by a combination of adaptation and mitigation measures in the forestry sector. It aims to increase forest/tree cover to the extent of 5 million hectares (Mha) and improve quality of forest/tree cover on another 5 Mha of forest/non-forest lands and support forest-based livelihoods of 3 million families and generate co-benefits through ES (Government of India 2010).

Thus, the community forest land recognised under FRA can be used for the purpose of compensatory afforestation or restoration under REDD+ only with informed consent of the communities and a decentralised mechanism for using CAMPA funds. India's forest and forest restoration can potentially move away from a top-down carbon centric model with the effective participation of local communities (Vijge and Gupta 2014; Murthy et al. 2018a).

India has also experimented with the world's first national inter-governmental ecological fiscal transfer (EFT) from central to local and state government to reward them for retaining forest cover. In 2014, India's 14th Finance Commission added forest cover to the formula that determines the amount of tax revenue the central government distributes annually to each of India's 29 states. It is estimated that, in four years, it would have distributed 6.9–12 billion USD per year to states in proportion to their 2013 forest cover, amounting to around 174–303 USD per hectare of forest per year (Busch and Mukherjee 2017). State governments in India now have a sizeable fiscal incentive based on extent of forest cover at the time of policy implementation, contributing to the achievement of India's climate mitigation and forest conservation goals. India's tax revenue distribution reform has created the world's first EFTs for forest conservation, and a potential model for other countries. However, it is to be noted that EFT is calculated based on a one-time estimate of forest cover prior to policy implementation, hence does not incentivise ongoing protection and this is a policy gap. It's still too early but its impact on trends in forest cover in the future and its ability to conserve forests without other investments and policy instruments is promising but untested (Busch and Mukherjee 2017; Busch 2018).

In order to build on the new promising policy developments on forest rights and fiscal incentives for forest conservation in India, incentivising ongoing protection, further investments in monitoring (Busch 2018), decentralisation (Somanathan et al. 2009) and promoting diverse non-agricultural forest and range of land-based livelihoods (e.g., sustainable non-timber forest product extraction, regulated pastures, carbon credits for forest regeneration on marginal agriculture land and ecotourism revenues) as part of individual and community forest tenure and rights are ongoing concerns. Decentralised sharing of CAMPA funds between government and local communities for forest restoration as originally suggested and filling in implementation gaps could help reconcile climate change mitigation through forest conservation, REDD+ and environmental justice (Vijge and Gupta 2014; Temper and Martinez-Alier 2013; Badola et al. 2013; Sun and Chaturvedi 2016; Murthy et al. 2018b; Chopra 2017; Ministry of Environment, Forest and Climate Change, and Ministry of Tribal Affairs, Government of India 2010).

7.4.7 Economic and financial instruments for adaptation, mitigation, and land

There is an urgent need to increase the volume of climate financing and bridge the gap between global adaptation needs and available funds (*medium confidence*) (Masson-Delmotte et al. 2018; Kissinger et al. 2019; Chambwera and Heal 2014), especially in relation to agriculture (FAO 2010). The land sector offers the potential to balance the synergies between mitigation and adaptation (Locatelli et al. 2016) – although context and unavailability of data sets makes cost comparisons between mitigation and adaptation difficult (UNFCCC 2018b). Estimates of adaptation costs range from 140 to 300 billion USD by 2030, and between 280 and 500 billion USD by 2050; (UNEP 2016). These figures vary according to methodologies and approaches (de Bruin et al. 2009; IPCC 2014 2014; OECD 2008; Nordhaus 1999; UNFCCC 2007; Plambeck et al. 1997).

7.4.7.1 Financing mechanisms for land mitigation and adaptation

There is a startling array of diverse and fragmented climate finance sources: more than 50 international public funds, 60 carbon markets, 6000 private equity funds, 99 multilateral and bilateral climate funds (Samuwai and Hills 2018). Most public finance for developing countries flows through bilateral and multilateral institutions such as the World Bank, the International Monetary Fund, International Finance Corporation, regional development banks, as well as specialised multilateral institutions such as the Global Environmental Fund, and the EU Solidarity Fund. Some governments have established state investment banks (SIBs) to close the financing gap, including the UK (Green Investment Bank), Australia (Clean Energy Finance Corporation) and in Germany (Kreditanstalt für Wiederaufbau) the Development Bank has been involved in supporting low-carbon finance (Geddes et al. 2018). The Green Climate Fund (GCF) now offers additional finance, but is still a new institution with policy gaps, a lengthy and cumbersome process related to approval (Brechin and Espinoza 2017; Khan and Roberts 2013; Mathy and Blanchard 2016), and challenges with adequate and sustained funding (Schalatek and Nakhooda 2013). Private adaptation finance exists, but is difficult to define, track, and coordinate (Nakhooda et al. 2016).

The amount of funding dedicated to agriculture, land degradation or desertification is very small compared to total climate finance (FAO 2010). Funding for agriculture (rather than mitigation) is accessed through the smaller adaptation funds (Lobell et al. 2013). Focusing on synergies, between mitigation, adaptation, and increased productivity, such as through climate-smart agriculture (CSA) (Lipper et al. 2014b) (Section 7.5.6), may leverage greater financial resources (Suckall et al. 2015; Locatelli et al. 2016). Payments for ecosystem services (Section 7.4.6) are another emerging area to encourage environmentally desirable practices, although they need to be carefully designed to be effective (Engel and Muller 2016).

The UNCCD established the Land Degradation Neutrality Fund (LDN Fund) to mobilise finance and scale-up land restoration and sustainable business models on restored land to achieve the target of a land degradation neutral world (SDG target 15.3) by 2030. The LDN Fund generates revenues from sustainable use of natural resources, creating green job opportunities, sequestering CO_2, and increasing food and water security (Cowie et al. 2018a; Akhtar-Schuster et al. 2017). The fund leverages public money to raise private capital for SLM and land restoration projects (Quatrini and Crossman 2018; Stavi and Lal 2015). Many small-scale projects are demonstrating that sustainable landscape management (Section 7.6.3) is key to achieving LDN, and it is also more financially viable in the long term than the unsustainable alternative (Tóth et al. 2018; Kust et al. 2017).

7.4.7.2 Instruments to manage the financial impacts of climate and land change disruption

Comprehensive risk management (Section 7.4.3.1) designs a portfolio of instruments which are used across a continuum of preemptive, planning and assessment, and contingency measures in order to bolster resilience (Cummins and Weiss 2016) and address limitations of any one instrument (Surminski 2016; Surminski et al. 2016; Linnerooth-bayer et al. 2019). Instruments designed and applied in isolation have shown short-term results, rather than sustained intended impacts (Vincent et al. 2018). Risk assessments limited to events and impacts on particular asset classes or sectors can misinform policy and drive misallocation of funding (Gallina et al. 2016; Jongman et al. 2014).

Comprehensive risk assessment combined with risk layering approaches that assign different instruments to different magnitude and frequency of events, have better potential to provide stability to societies facing disruption (Mechler et al. 2014; Surminski et al. 2016). Governments and citizens define limits of what they consider acceptable risks, risks for which market or other solutions can be developed and catastrophic risks that require additional public protection and intervention. Different financial tools may be used for these different categories of risk or phases of the risk cycle (preparedness, relief, recovery, reconstruction).

In order to protect lives and livelihoods early action is critical, including a coordinated plan for action agreed in advance, a fast, evidence-based decision-making process, and contingency financing to ensure that the plan can be implemented (Clarke and Dercon 2016a). Forecast-based finance mechanisms incorporate these principles, using climate or other indicators to trigger funding and action prior to a shock (Wilkinson 2018). Forecast-based mechanisms can be linked with social protection systems by providing contingent scaled-up finance quickly to vulnerable populations following disasters, enhancing scalability, timeliness, predictability and adequacy of social protection benefits (Wilkinson 2018; Costella et al. 2017b; World Food Programme 2018).

Measures in advance of risks set aside resources before negative impacts related to adverse weather, climatic stressors, and land changes occur. These tools are frequently applied in extreme event, rapid onset contexts. These measures are the main instruments for reducing fatalities and limiting damage from extreme climate and land change events (Surminski et al. 2016). Finance tools in advance of risk include insurance (macro, meso, micro), green bonds, and forecast-based finance (Hunzai et al. 2018).

There is *high confidence* that insurance approaches that are designed to effectively reduce and communicate risks to the public and beneficiaries, designed to reduce risk and foster appropriate adaptive responses, and provide value in risk transfer, improve economic stability and social outcomes in both higher – and lower-income contexts (Kunreuther and Lyster 2016; Outreville 2011b; Surminski et al. 2016; Kousky et al. 2018b), bolster food security, help keep children in school, and help safeguard the ability of low-income households to pay for essentials like medicines (Shiferaw et al. 2014; Hallegatte et al. 2017).

Low-income households show demand for affordable risk transfer tools, but demand is constrained by liquidity, lack of assets, financial and insurance literacy, or proof of identity required by institutions in the formal sector (Eling et al. 2014; Cole 2015; Cole et al. 2013; Ismail et al. 2017). Microinsurance participation takes many forms, including through mobile banking (Eastern Africa, Bangladesh), linked with social protection or other social stabilisation programmes (Ethiopia, Pakistan, India), through flood or drought protection schemes (Indonesia, the Philippines, the Caribbean, and Latin America), often in the form of weather index insurance. The insurance industry faces challenges due to low public awareness of how insurance works. Other challenges include risk, low capacity in financial systems to administer insurance, data deficits, and market imperfections (Mechler et al. 2014; Feyen et al. 2011; Gallagher 2014; Kleindorfer et al. 2012; Lazo et al.; Meyer and Priess 2014; Millo 2016).

Countries also request grant assistance, and contingency debt finance that includes dedicated funds, set aside for unpredictable climate-related disasters, household savings, and loans with 'catastrophe risk deferred drawdown option' (which allows countries to divert loans from development objectives such as health, education, and infrastructure to make immediate disbursement of funds in the event of a disaster) (Kousky and Cooke 2012; Clarke and Dercon 2016b). Contingency finance is suited to manage frequently occurring, low-impact events (Campillo et al. 2017; Mahul and Ghesquiere 2010; Roberts 2017) and may be linked with social protection systems. These instruments are limited by uncertainty surrounding the size of contingency fund reserves, given unpredictable climate disasters (Roberts 2017) and lack of borrowing capacity of a country (such as small island states) (Mahul and Ghesquiere 2010).

In part because of its link with debt burden, contingency, or post-event finance can disrupt development and is not suitable for higher consequence events and processes such as weather extremes or structural changes associated with climate and land change. Post-event finance of negative impacts such as sea level rise, soil salinisation, depletion of groundwater, and widespread land degradation, is likely to become infeasible for multiple, high-cost events and processes. There is *high confidence* that post-extreme event assistance may face more severe limitations, given the impacts of climate change (Linnerooth-bayer et al. 2019; Surminski et al. 2016; Deryugina 2013; Dillon et al. 2014; Clarke 2016; Shreve and Kelman 2014; Von Peter et al. 2012).

In a catastrophe risk pool, multiple countries in a region pool risks in a diversified portfolio. Examples include African Risk Capacity (ARC), the Caribbean Catastrophe Risk Insurance Facility (CCRIF), and the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) (Bresch et al. 2017; Iyahen and Syroka 2018). ARC payouts have been used to assist over 2.1 million food insecure people and provide more than 900,000 cattle with subsidised feed in the affected countries (Iyahen and Syroka 2018). ARC has also developed the Extreme Climate Facility, which is designed to complement existing bilateral, multilateral and private sources of finance to enable proactive adaptation (Vincent et al. 2018). It provides beneficiaries the opportunity to increase their benefit by reducing exposure to risk through adaptation and risk reduction measures, thus side-stepping 'moral hazard' problems sometimes associated with traditional insurance.

Governments pay coupon interest when purchasing catastrophe (CAT) bonds from private or corporate investors. In the case of the predefined catastrophe, the requirement to pay the coupon interest or repay the principal may be deferred or forgiven (Nguyen and Lindenmeier 2014). CAT bonds are typically short-term instruments (three to five years) and the payout is triggered once a particular threshold of disaster/damage is passed (Härdle and Cabrera 2010; Campillo et al. 2017; Estrin and Tan 2016; Hermann et al. 2016; Michel-Kerjan 2011; Roberts 2017). The primary advantage of CAT bonds is their ability to quickly disburse money in the event of a catastrophe (Estrin and Tan 2016). Green bonds, social impact bonds, and resilience bonds are other instruments that can be used to fund land-based interventions. However, there are significant barriers for developing country governments to enter into the bond market: lack of familiarity with the instruments; lack of capacity and resources to deal with complex legal arrangements; limited or non-existent data and modelling of disaster exposure; and other political disincentives linked to insurance. For these reasons, the utility and application of bonds is currently largely limited to higher-income developing countries (Campillo et al. 2017; Le Quesne 2017).

7.4.7.3 Innovative financing approaches for transition to low-carbon economies

Traditional financing mechanisms have not been sufficient and thereby leave a gap in facilitating a rapid transition to a low-carbon economy or building resilience (Geddes et al. 2018). More recently there have been developments in more innovative mechanisms, including crowdfunding (Lam and Law 2016), often supported by national governments (in the UK through regulatory and tax support) (Owen et al. 2018). Crowdfunding has no financial intermediaries and thus low transaction costs, and the projects have a greater degree of independence than bank or institution funding (Miller et al. 2018). Other examples of innovative mechanisms are community shares for local projects, such as renewable energy (Holstenkamp and Kahla 2016), or Corporate Power Purchase Agreements (PPAs) used by companies such as Google and Apple to purchase renewable energy directly or virtually from developers (Miller et al. 2018). Investing companies benefit from avoiding unpredictable price fluctuations as well as increasing their environmental credentials. A second example is auctioned price floors, or subsidies that offer a guaranteed price for future emission reductions, currently being trialled in developing countries, by the World Bank Group, known as the Pilot Auction Facility for Methane and Climate Change Mitigation (PAF) (Bodnar et al. 2018). Price floors can maximise the climate impact per public dollar while incentivising private investment in low-carbon technologies, and ideally would be implemented in conjunction with complementary policies such as carbon pricing.

In order for climate finance to be as effective and efficient as possible, cooperation between private, public and third sectors (e.g., non-governmental organisations (NGOs), cooperatives, and community groups) is more likely to create an enabling environment for innovation (Owen et al. 2018). While innovative private sector approaches are making significant progress, the existence of a stable policy environment that provides certainty and incentives for long-term private investment is critical.

7.4.8 Enabling effective policy instruments – policy portfolio coherence

An enabling environment for policy effectiveness includes: (i) the development of comprehensive policies, strategies and programmes (Section 7.4); (ii) human and financial resources to ensure that policies, programmes and legislation are translated into action; (iii) decision-making that draws on evidence generated from functional information systems that make it possible to monitor trends, track and map actions, and assess impact in a manner that is timely and comprehensive (Section 7.5); (iv) governance coordination mechanisms and partnerships; and (v) a long-term perspective in terms of response options, monitoring, and maintenance (FAO 2017a) (Section 7.6).

A comprehensive consideration of policy portfolios achieves sustainable land and climate management (*medium confidence*) (Mobarak and Rosenzweig 2013; Stavropoulou et al. 2017; Jeffrey et al. 2017; Howlett and Rayner 2013; Aalto et al. 2017; Brander and Keith 2015; Williams and Abatzoglou 2016; Linnerooth-Bayer and Hochrainer-Stigler 2015; FAO 2017b; Bierbaum and Cowie 2018). Supporting the study of enabling environments, the study of policy mixes has emerged in the last decade in regards to the mix or set of instruments that interact together and are aimed at achieving policy objectives in a dynamic setting (Reichardt et al. 2015). This includes studying the ultimate objectives of a policy mix – such as biodiversity (Ring and Schröter-Schlaack 2011) – the interaction of policy instruments within the mix (including climate change mitigation and energy (del Río and Cerdá 2017)) (see Trade-offs and synergies, Section 7.5.6), and the dynamic nature of the policy mix (Kern and Howlett 2009).

Studying policy mixes allows for a consideration of policy coherence that is broader than the study of discrete policy instruments in rigidly defined sectors, but entails studying policy in relation to the links and dependencies among problems and issues (FAO 2017b). Consideration of policy coherence is a new approach, rejecting simplistic solutions, but acknowledging inherently complex processes involving collective consideration of public and private actors in relation to policy analysis (FAO 2017b). A coherent, consistent mix of policy instruments can solve complex policy problems (Howlett and Rayner 2013) as it involves lateral, integrative, and holistic thinking in defining and solving problems (FAO 2017b). Such a consideration of policy coherence is required to achieve sustainable development (FAO 2017b; Bierbaum and Cowie 2018). Consideration of policy coherence potentially addresses three sets of challenges: challenges that exist with assessing multiple hazards and sectors (Aalto et al. 2017; Brander and Keith 2015; Williams and Abatzoglou 2016); challenges in mainstreaming adaptation and risk management into ongoing development planning and decision-making (Linnerooth-Bayer and Hochrainer-Stigler 2015); and challenges in scaling-up community and ecosystem-based initiatives in countries overly focused on sectors, instead of sustainable use of biodiversity and ES (Reid 2016). There is a gap in integrated consideration of adaptation, mitigation, climate change policy and development. A study in Indonesia found that, while internal policy coherence between mitigation and adaptation is increasing, external policy coherence between climate change policy and development objectives is still required (Di Gregorio et al. 2017).

There is *medium evidence* and *high agreement* that a suite of agricultural business risk programmes (which would include crop insurance and income stability programmes) increase farm financial performance, reduce risk, and also reinforce incentives to adopt stewardship practices (beneficial management practices) improving the environment (Jeffrey et al. 2017). Consideration of the portfolio of instruments responding to climate change and its associated risks, and the interaction of policy instruments, improve agricultural producer livelihoods (Hurlbert 2018b). In relation to hazards, or climate-related extremes (Section 7.4.3), the policy mix has been found to be a key determinant of the adaptive capacity of agricultural producers. In relation to drought, the mix of policy instruments including crop insurance, SLM practices, bankruptcy and insolvency, co-management of community in water and disaster planning, and water infrastructure programmes are effective at responding to drought (Hurlbert 2018b; Hurlbert and Mussetta 2016; Hurlbert and Pittman 2014; Hurlbert and Montana 2015; Hurlbert 2015a; Hurlbert and Gupta 2018). Similarly, in relation to flood, the mix of policy instruments including flood zone mapping, land-use planning, flood zone building restrictions, business and crop insurance, disaster assistance payments, preventative instruments, such as environmental farm planning (including soil and water management (Chapter 6)) and farm infrastructure projects, and recovery from debilitating flood losses, ultimately through bankruptcy, are effective at responding to flood (Hurlbert 2018a) (see Case study: Flood and flood security in Section 7.6.3).

In respect of land conservation and management goals, consideration of differing strengths and weakness of instruments is necessary. While direct regulation may secure effective minimum standards of biodiversity conservation and critical ES provision, economic instruments may achieve reduced compliance costs as costs are borne by policy addressees (Rogge and Reichardt 2016). In relation to GHG emissions and climate mitigation, a comprehensive mix of instruments targeted at emissions reductions, learning, and R&D is effective (*high confidence*) (Fischer and Newell 2008). The policy coherence between climate policy and public financeis critical in ensuring the efficiency, effectiveness and equity of mitigation policy, and ultimately to make stringent mitigation policy more feasible (Siegmeier et al. 2018). Recycling carbon tax revenue to support clean energy technologies can decrease losses from unilateral carbon mitigation targets, with complementary technology polices (Corradini et al. 2018).

When evaluating a new policy instrument, its design in relation to achieving an environmental goal or solving a land and climate change issue, includes consideration of how the new instrument will interact with existing instruments operating at multiple levels (international, regional, national, sub-national, and local) (Ring and Schröter-Schlaack 2011) (Section 7.4.1).

7.4.9 Barriers to implementing policy responses

There are barriers to implementing the policy instruments that arise in response to the risks from climate-land interactions. Such barriers to climate action help determine the degree to which society can achieve its sustainable development objectives (Dow et al. 2013; Langholtz et al. 2014; Klein et al. 2015). However, some policies can also be seen as being designed specifically to overcome barriers, while some cases may actually create or strengthen barriers to climate action (Foudi and Erdlenbruch 2012; Linnerooth-Bayer and Hochrainer-Stigler 2015). The concept of barriers to climate action is used here in a sense close to that of 'soft limits' to adaptation (Klein, et al. 2014). 'Hard limits' by contrast are seen as primarily biophysical. Predicted changes in the key factors of crop growth and productivity – temperature, water, and soil quality – are expected to pose limits to adaptation in ways that affect the world population's ability to get enough food in the future (Altieri et al. 2015; Altieri and Nicholls 2017).

This section assesses research on barriers specific to policy implementation in adaptation and mitigation respectively, then addresses the cross-cutting issue of inequality as a barrier to climate action, including the particular cases of corruption and elite capture, before assessing how policies on climate and land can be used to overcome barriers.

7.4.9.1 Barriers to adaptation

There are human, social, economic, and institutional barriers to adaptation to land-climate challenges as described in Table 7.4 (*medium evidence*, *high agreement*). Considerable literature exists around changing behaviours through response options targeting social and cultural barriers (Rosin 2013; Eakin 2016; Marshall et al. 2012) (Chapter 6).

Since the publication of the IPCC's Fifth Assessment Report (AR5) (IPCC 2014), research is emerging, examining the role of governance, institutions and (in particular) policy instruments, in creating or overcoming barriers to adaptation to land and climate change in the land-use sector (Foudi and Erdlenbruch 2012; Linnerooth-Bayer and Hochrainer-Stigler 2015). Evidence shows that understanding the local context and targeted approaches are generally most successful (Rauken et al. 2014). Understanding the nature of constraints to adaptation is critical in determining how barriers may be overcome. Formal institutions (rules, laws, policies) and informal institutions (social and cultural norms and shared understandings) can be barriers and enablers of climate adaptation (Jantarasami et al. 2010).

Governments play a key role in intervening and confronting existing barriers by changing legislation, adopting policy instruments, providing additional resources, and building institutions and knowledge exchange (Ford and Pearce 2010; Measham et al. 2011; Mozumder et al. 2011; Storbjörk 2010). Understanding institutional barriers is important in addressing barriers (*high confidence*). Institutional barriers may exist due to the path-dependent nature of institutions governing natural resources and public good, bureaucratic structures that undermine horizontal and vertical integration (Section 7.6.2), and lack of policy coherence (Section 7.4.8).

7.4.9.2 Barriers to land-based climate mitigation

Barriers to land-based mitigation relate to full understanding of the permanence of carbon sequestration in soils or terrestrial biomass, the additionality of this storage, its impact on production and production shifts to other regions, measurement and monitoring systems and costs (Smith et al. 2007). Agricultural producers are more willing to expand mitigation measures already employed (including efficient and effective management of fertiliser, including manure and slurry) and less favourable to those not employed, such as using dietary additives, adopting genetically improved animals, or covering slurry tanks and lagoons (Feliciano et al. 2014). Barriers identified in land-based mitigation include physical environmental constraints such as lack of information, education, and suitability for size and location of farm. For instance, precision agriculture is not viewed as efficient in small-scale farming (Feliciano et al. 2014).

Property rights may be a barrier when there is no clear single-party land ownership to implement and manage changes (Smith et al. 2007). In forestry, tenure arrangements may not distribute obligations and incentives for carbon sequestration effectively between public management agencies and private agents with forest licences. Including carbon in tenure and expanding the duration of tenure may provide stronger incentive for tenure holders to manage carbon as well as timber values (Williamson and Nelson 2017). Effective policy will require answers as to the current status of agriculture in regard to GHG emissions, the degree that emissions are to change, the best pathway to achieve the change, and an ability to know when the target level of change is achieved (Smith et al. 2007). Forest governance may not have the structure to advance mitigation and adaptation. Currently top-down traditional modes do not have the flexibility or responsiveness to deal with the complex, dynamic, spatially diverse, and uncertain features of climate change (Timberlake and Schultz 2017; Williamson and Nelson 2017).

In respect of forest mitigation, two main institutional barriers have been found to predominate. First, forest management institutions do not consider climate change to the degree necessary for enabling effective climate response, and do not link adaptation and mitigation. Second, institutional barriers exist if institutions are not forward looking, do not enable collaborative adaptive management, do not

Table 7.4 | Soft barriers and limits to adaptation.

Category	Description	References
Human	– Cognitive and behavioural obstacles – Lack of knowledge and information	Hornsey et al. 2016; Prokopy et al. 2015; Wreford et al. 2017
Social	– Undermined participation in decision-making and social equity	Burton et al. 2008; Laube et al. 2012
Economic	– Market failures and missing markets: transaction costs and political economy; ethical and distributional issues – Perverse incentives – Lack of domestic funds; inability to access international funds	Chambwera et al. 2014b; Wreford et al. 2017; Rochecouste et al. 2015; Baumgart-Getz et al. 2012
Institutional	– Mal-coordination of policies and response options; unclear responsibility of actors and leadership; misuse of power; all reducing social learning – Government failures – Path-dependent institutions	Oberlack 2017; Sánchez et al. 2016; Greiner and Gregg 2011
Technological	– Systems of mixed crop and livestock – Polycultures	Nalau and Handmer 2015

promote flexible approaches that are reversible as new information becomes available, do not promote learning and allow for diversity of approaches that can be tailored to different local circumstances (Williamson and Nelson 2017).

Land-based climate mitigation through expansions and enhancements in agriculture, forestry and bioenergy has great potential but also poses great risks; its success will therefore require improved land-use planning, strong governance frameworks and coherent and consistent policies. 'Progressive developments in governance of land and modernisation of agriculture and livestock and effective sustainability frameworks can help realise large parts of the technical bioenergy potential with low associated GHG emissions' (Smith et al. 2014b, p. 97).

7.4.9.3 Inequality

There is *medium evidence* and *high agreement* that one of the greatest challenges for land-based adaptation and SLM is posed by inequalities that influence vulnerability and coping and adaptive capacity – including age, gender, wealth, knowledge, access to resources and power (Kunreuther et al. 2014; IPCC 2012; Olsson et al. 2014). Gender is the dimension of inequality that has been the focus of most research, while research demonstrating differential impacts, vulnerability and adaptive capacity based on age, ethnicity and indigeneity is less well developed (Olsson et al. 2015a). Cross-Chapter Box 11 in Chapter 7 sets out both the contribution of gender relations to differential vulnerability and available policy instruments for greater gender inclusivity.

One response to the vulnerability of poor people and other categories differentially affected is effective and reliable social safety nets (Jones and Hiller 2017). Social protection coverage is low across the world and informal support systems continue to be the key means of protection for a majority of the rural poor and vulnerable (Stavropoulou et al. 2017) (Section 7.4.2). However, there is a gap in knowledge in understanding both positive and negative synergies between formal and informal systems of social protection and how local support institutions might be used to implement more formal forms of social protection (Stavropoulou et al. 2017).

7.4.9.4 Corruption and elite capture

Inequalities of wealth and power can allow processes of corruption and elite capture (where public resources are used for the benefit of a few individuals in detriment to the larger populations) which can affect both adaptation and mitigation actions, at levels from the local to the global that, in turn, risk creating inequitable or unjust outcomes (Sovacool 2018) (*limited evidence*, *medium agreement*). This includes risks of corruption in REDD+ processes (Sheng et al. 2016; Williams and Dupuy 2018) and of corruption or elite capture in broader forest governance (Sundström 2016; Persha and Andersson 2014), as well as elite capture of benefits from planned adaptation at a local level (Sovacool 2018).

Peer-reviewed empirical studies that focus on corruption in climate finance and interventions, particularly at a local level, are rare, due in part to the obvious difficulties of researching illegal and clandestine activity (Fadairo et al. 2017). At the country level, historical levels of corruption are shown to affect current climate polices and global cooperation (Fredriksson and Neumayer 2016). Brown (2010) sees three likely inlets of corruption into REDD+: in the setting of forest baselines, the reconciliation of project and natural credits, and the implementation of control of illegal logging. The transnational and north-south dimensions of corruption are highlighted by debates on which US legislative instruments (e.g., the Lacey Act, the Foreign Corrupt Practices Act) could be used to prosecute the northern corporations that are involved in illegal logging (Gordon 2016; Waite 2011).

Fadairo et al. (2017) carried out a structured survey of perceptions of households in forest-edge communities served by REDD+, as well as those of local officials, in south eastern Nigeria. They report high rates of agreement that allocation of carbon rights is opaque and uncertain, distribution of benefits is untimely, uncertain and unpredictable, and the REDD+ decision-making process is vulnerable to political interference that benefits powerful individuals. Only 35% of respondents had an overall perception of transparency in REDD+ process as 'good'. Of eight institutional processes or facilities previously identified by the government of Nigeria and international agencies as indicators of commitment to transparent and equitable governance, only three were evident in the local REDD+ office as 'very functional' or 'fairly functional'.

At the local level, the risks of corruption and elite capture of the benefits of climate action are high in decentralised regimes (Persha and Andersson 2014). Rahman (2018) discusses elicitation of bribes (by local-level government staff) and extortion (by criminals) to allow poor rural people to gather forest products. The results are a general undermining of households' adaptive capacity and perverse incentives to over-exploit forests once bribes have been paid, leading to over-extraction and biodiversity loss. Where there are pre-existing inequalities and conflict, participation processes need careful management and firm external agency to achieve genuine transformation and avoid elite capture (Rigon 2014). An illustration of the range of types of elite capture is given by Sovacool (2018) for adaptation initiatives including coastal afforestation, combining document review and key informant interviews in Bangladesh, with an analytical approach from political ecology. Four processes are discussed: enclosure, including land grabbing and preventing the poor establishing new land rights; exclusion of the poor from decision-making over adaptation; encroachment on the resources of the poor by new adaptation infrastructure; and entrenchment of community disempowerment through patronage. The article notes that observing these processes does not imply they are always present, nor that adaptation efforts should be abandoned.

7.4.9.5 Overcoming barriers

Policy instruments that strengthen agricultural producer assets or capital reduce vulnerability and overcome barriers to adaptation (Hurlbert 2018b, 2015b). Additional factors like formal education and knowledge of traditional farming systems, secure tenure rights, access to electricity and social institutions in rice-farming areas of Bangladesh have played a positive role in reducing adaptation barriers (Alam 2015). A review of more than 168 publications over 15 years about adaptation of water resources for irrigation in Europe found the highest potential for action is in improving adaptive capacity and responding to changes in water demands, in conjunction with alterations in current water policy, farm extension training, and viable financial instruments (Iglesias and Garrote 2015). Research on the Great Barrier Reef, the Olifants River in Southern Africa, and fisheries in Europe, North America, and the Antarctic Ocean, suggests that the leading factor in harnessing the adaptive capacity of ecosystems is to reduce human stressors by enabling actors to collaborate across diverse interests, institutional settings, and sectors (Biggs et al. 2017; Schultz et al. 2015; Johnson and Becker 2015). Fostering equity and participation are correlated with the efficacy of local adaptation to secure food and livelihood security (Laube et al. 2012). In this chapter, we examine the literature surrounding appropriate policy instruments, decision-making, and governance practices to overcome limits and barriers to adaptation.

Incremental adaptation consists of actions where the central aim is to maintain the essence and integrity of a system or process at a given site, whereas transformational adaptation changes the fundamental attributes of a system in response to climate and its effects; the former is characterised as doing different things and the latter, doing things differently (Noble et al. 2014). Transformational adaptation is necessary in situations where there are hard limits to adaptation or it is desirable to address deficiencies in sustainability, adaptation, inclusive development and social equity (Kates et al. 2012; Mapfumo et al. 2016). In other situations, incremental changes may be sufficient (Hadarits et al. 2017).

Cross-Chapter Box 11 | Gender in inclusive approaches to climate change, land and sustainable development

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Gender is a key axis of social inequality that intersects with other systems of power and marginalisation – including race, culture, class/socio-economic status, location, sexuality, and age – to cause unequal experiences of climate change vulnerability and adaptive capacity. However, 'policy frameworks and strong institutions that align development, equity objectives, and climate have the potential to deliver "triple-wins"' (Roy et al. 2018), including enhanced gender equality. Gender in relation to this report is introduced in Chapter 1, referred to as a leverage point in women's participation in decisions relating to land desertification (Section 3.6.3), land degradation (Section 4.1.6), food security (Section 5.2.5.1), and enabling land and climate response options (Section 6.1.2.2).

Focusing on 'gender' as a relational and contextual construct can help avoid homogenising women as a uniformly and consistently vulnerable category (Arora-Jonsson 2011; Mersha and Van Laerhoven 2016; Ravera et al. 2016). There is high agreement that using a framework of intersectionality to integrate gender into climate change research helps to recognise overlapping and interconnected systems of power (Djoudi et al. 2016; Fletcher 2018; Kaijser and Kronsell 2014; Moosa and Tuana 2014; Thompson-Hall et al. 2016), which create particular inequitable experiences of climate change vulnerability and adaptation. Through this framework, both commonalities and differences may be found between the experiences of rural and urban women, or between women in high-income and low-income countries, for example.

In rural areas, women generally experience greater vulnerability than men, albeit through different pathways (Djoudi et al., 2016; Goh, 2012; Jost et al., 2016; Kakota, Nyariki, Mkwambisi, & Kogi-Makau, 2011). In masculinised agricultural settings of Australia and Canada, for example, climate adaptation can increase women's work on- and off-farm, but without increasing recognition for women's undervalued contributions (Alston et al. 2018a; Fletcher and Knuttila 2016). A study in rural Ethiopia found that male-headed households had access to a wider set of adaptation measures than female-headed households (Mersha and Van Laerhoven 2016).

Due to engrained patriarchal social structures and gendered ideologies, women may face multiple barriers to participation and decision-making in land-based adaptation and mitigation actions in response to climate change (*high confidence*) (Alkire et al. 2013a; Quisumbing et al. 2014). These barriers include: (i) disproportionate responsibility for unpaid domestic work, including care-giving activities (Beuchelt and Badstue 2013) and provision of water and firewood (UNEP, 2016); (ii) risk of violence in both public and private spheres, which restricts women's mobility for capacity-building activities and productive work outside the home (Day et al., 2005; Jost et al., 2016; UNEP, 2016); (iii) less access to credit and financing (Jost et al. 2016); (iv) lack of organisational social capital, which may help in accessing credit (Carroll et al. 2012); (v) lack of ownership of productive assets and resources (Kristjanson et al., 2014;

Cross-Chapter Box 11 (continued)

Meinzen-Dick et al., 2010), including land. Constraints to land access include not only state policies, but also customary laws (Bayisenge 2018) based on customary norms and religion that determine women's rights (Namubiru-Mwaura 2014a).

Differential vulnerability to climate change is related to inequality in rights-based resource access, established through formal and informal tenure systems. In only 37% of 161 developing and developed countries do men and women have equal rights to use and control land, and in 59% customary, traditional, and religious practices discriminate against women (OECD 2014), even if the law formally grants equal rights. Women play a significant role in agriculture, food security and rural economies globally, forming 43% of the agricultural labour force in developing countries (FAO, IFAD, UNICEF, & WHO, 2018, p. 102), ranging from 25% in Latin America (FAO, 2017, p. 89) to nearly 50% in Eastern Asia and Central and South Europe (FAO, 2017, p. 88) and 47% in Sub-Saharan Africa (FAO, 2017, pp. 88). Further, the share of women in agricultural employment has been growing in all developing regions except East Asia and Southeast Asia (FAO, 2017, p. 88). At the same time, women constitute less than 5% of landholders (with legal rights and/or use-rights (Doss et al. 2018a) in North Africa and West Asia, about 15% in Sub-Saharan Africa, 12% in Southern and Southeastern Asia, 18% in Latin America and Caribbean (FAO 2011b, p. 25), 10% in Bangladesh, 4% in Nigeria (FAO 2015c). Patriarchal structures and gender roles can also affect women's control over land in developed countries (Carter 2017; Alston et al. 2018b). Thus, longstanding gender inequality in land rights, security of tenure, and decision-making may constrict women's adaptation options (Smucker and Wangui 2016).

Adaptation options related to land and climate (see Chapter 6) may produce environment and development trade-offs as well as social conflicts (Hunsberger et al. 2017) and changes with gendered implications. Women's strong presence in agriculture provides an opportunity to bring gender dimensions into climate change adaptation, particularly regarding food security (Glemarec 2017; Jost et al. 2016; Doss et al. 2018b). Some studies point to a potentially emancipatory role played by adaptation interventions and strategies, albeit with some limitations depending on context. For example, in developing contexts, male out-migration may cause women in socially disadvantaged groups to engage in new livelihood activities, thus challenging gendered roles (Djoudi and Brockhaus 2011; Alston 2006). Collective action and agency of women in farming households, including widows, have led to prevention of crop failure, reduced workload, increased nutritional intake, increased sustainable water management, diversified and increased income and improved strategic planning (Andersson and Gabrielsson 2012). Women's waged labour can help stabilise income from more land- and climate-dependent activities such as agriculture, hunting, or fishing (Alston et al., 2018; Ford and Goldhar, 2012). However, in developed contexts like Australia, women's participation in off-farm employment may exacerbate existing masculinisation of agriculture (Clarke and Alston 2017).

Literature suggests that land-based mitigation measures may lead to land alienation, either through market or appropriation (acquisition) by the government, may interfere with traditional livelihoods in rural areas, and lead to decline in women's livelihoods (Hunsberger et al. 2017). If land alienation is not prevented, existing inequities and social exclusions may be reinforced (medium agreement) (Mustalahti and Rakotonarivo 2014; Chomba et al. 2016; Poudyal et al. 2016). These activities also can lead to land grabs, which remain a focal point for research and local activism (Borras Jr. et al. 2011; White et al. 2012; Lahiff 2015). Cumulative effects of land-based mitigation measures may put families at risk of poverty. In certain contexts, they lead to increased conflicts. In conflict situations, women are at risk of personal violence, including sexual violence (UNEP, 2016).

Policy instruments for gender-inclusive approaches to climate change, land and sustainable development

Integrating, or mainstreaming, gender into land and climate change policy requires assessments of gender-differentiated needs and priorities, selection of appropriate policy instruments to address barriers to women's sustainable land management (SLM), and selection of gender indicators for monitoring and assessment of policy (medium confidence) (Huyer et al. 2015a; Alston 2014). Important sex-disaggregated data can be obtained at multiple levels, including the intra-household level (Seager 2014; Doss et al. 2018b), village- and plot-level information (Theriault et al. 2017a), and through national surveys (Agarwal 2018a; Doss et al. 2015a). Gender-disaggregated data provides a basis for selecting, monitoring and reassessing policy instruments that account for gender-differentiated land and climate change needs (medium confidence) (Rao 2017a; Arora-Jonsson 2014; Theriault et al. 2017b; Doss et al. 2018b). While macro-level data can reveal ongoing gender trends in SLM, contextual data are important for revealing intersectional aspects, such as the difference made by family relations, socio-economic status, or cultural practices about land use and control (Rao 2017a; Arora-Jonsson 2014; Theriault et al. 2017b), as well as on security of land holding (Doss et al. 2018b). Indices such as the Women's Empowerment in Agriculture Index (Alkire et al. 2013b) may provide useful guidelines for quantitative data collection on gender and SLM, while qualitative studies can reveal the nature of agency and whether policies are likely to be accepted, or not, in the context of local structures, meanings, and social relations (Rao 2017b).

Cross-Chapter Box 11 (continued)

Women's economic empowerment, decision-making power and voice is a necessity in SLM decisions (Mello and Schmink 2017a; Theriault et al. 2017b). Policies that address barriers include: gender considerations as qualifying criteria for funding programmes or access to financing for initiatives; government transfers to women under the auspices of anti-poverty programmes; spending on health and education; and subsidised credit for women (medium confidence) (Jagger and Pender 2006; Van Koppen et al. 2013a; Theriault et al. 2017b; Agarwal 2018b). Training and extension for women to facilitate sustainable practices is also important (Mello and Schmink 2017b; Theriault et al. 2017b). Such training could be built into existing programmes or structures, such as collective microenterprise (Mello and Schmink 2017b). Huyer et al. (2015) suggest that information provision (e.g., information about SLM) could be effectively dispersed through women's community-based organisations, although not in such a way that it overwhelms these organisations or supersedes their existing missions. SLM programmes could also benefit from intentionally engaging men in gender-equality training and efforts (Fletcher 2017), thus recognising the relationality of gender. Recognition of the household level, including men's roles and power relations, can help avoid the decontextualised and individualistic portrayal of women as purely instrumental actors (Rao 2017b).

Technology, policy, and programmes that exacerbate women's workloads or reinforce gender stereotypes (MacGregor 2010; Huyer et al. 2015b), or which fail to recognise and value the contributions women already make (Doss et al. 2018b), may further marginalise women. Accordingly, some studies have described technological and labour interventions that can enhance sustainability while also decreasing women's workloads; for example, Vent et al. (2017) described the system of rice intensification as one such intervention. REDD+ initiatives need to be aligned with the Sustainable Development Goals (SDGs) to achieve complementary synergies with gender dimensions.

Secure land title and/or land access and control for women increases SLM by increasing women's conservation efforts, increasing their productive and environmentally beneficial agricultural investments, such as willingness to engage in tree planting and sustainable soil management (high confidence) as well as improving cash incomes (Higgins et al. 2018; Agarwal 2010; Namubiru-Mwaura 2014b; Doss et al. 2015b; Van Koppen et al. 2013b; Theriault et al. 2017b; Jagger and Pender 2006). According FAO (2011b, p. 5), if women had the same access to productive resources as men, the number of hungry people in the world could be reduced by 12–17%. Policies promoting secure land title include legal reforms at multiple levels, including national laws on land ownership, legal education, and legal aid for women on land ownership and access (Argawal 2018). Policies to increase women's access to land could occur through three main avenues of land acquisition: inheritance/family (Theriault et al. 2017b), state policy, and the market (Agarwal 2018). Rao (2017) recommends framing land rights as entitlements rather than as instrumental means to sustainability. This reframing may address persistent, pervasive gender inequalities (FAO 2015d).

7.5 Decision-making for climate change and land

The risks posed by climate change generate considerable uncertainty and complexity for decision-makers responsible for land-use decisions (*robust evidence*, *high agreement*). Decision-makers balance climate ambitions, encapsulated in the NDCs, with other SDGs, which will differ considerably across different regions, sociocultural conditions and economic levels (Griggs et al. 2014). The interactions across SDGs also factor into decision-making processes (Nilsson et al. 2016b). The challenge is particularly acute in least developed countries where a large share of the population is vulnerable to climate change. Matching the structure of decision-making processes to local needs while connecting to national strategies and international regimes is challenging (Nilsson and Persson 2012). This section explores methods of decision-making to address the risks and inter-linkages outlined in the above sections. As a result, this section outlines policy inter-linkages with SDGs and NDCs, trade-offs and synergies in specific measures, possible challenges as well as opportunities going forward.

Even in cases where uncertainty exists, there is *medium evidence* and *high agreement* in the literature that it need not present a barrier to taking action, and there are growing methodological developments and empirical applications to support decision-making. Progress has been made in identifying key sources of uncertainty and addressing them (Farber 2015; Lawrence et al. 2018; Bloemen et al. 2018). Many of these approaches involve principles of robustness, diversity, flexibility, learning, or choice editing (Section 7.5.2).

Since the IPCC's Fifth Assessment Report (*Foundations for Decision Making*) chapter on Contexts for Decision-making (Jones et al. 2014) considerable advances have been made in decision-making under uncertainty, both conceptually and in economics (Section 7.5.2), and in the social/qualitative research areas (Sections 7.5.3 and 7.5.4). In the land sector, the degree of uncertainty varies and is particularly challenging for climate change adaptation decisions (Hallegatte 2009; Wilby and Dessai 2010). Some types of agricultural production decisions can be made in short timeframes as changes are observed, and will provide benefits in the current time period (Dittrich et al. 2017).

7.5.1 Formal and informal decision-making

Informal decision-making facilitated by open platforms can solve problems in land and resource management by allowing evolution and adaptation, and incorporation of local knowledge (*medium confidence*) (Malogdos and Yujuico 2015a; Vandersypen et al. 2007). Formal centres of decision-making are those that follow fixed procedures (written down in statutes or moulded in an organisation backed by the legal system) and structures (Onibon et al. 1999). Informal centres of decision-making are those following customary norms and habits based on conventions (Onibon et al. 1999) where problems are ill-structured and complex (Waddock 2013).

7.5.1.1 Formal Decision Making

Formal decision-making processes can occur at all levels, including the global, regional, national and sub-national levels (Section 7.4.1). Formal decision-making support tools can be used, for example, by farmers, to answer 'what-if' questions as to how to respond to the effects of changing climate on soils, rainfall and other conditions (Wenkel et al. 2013).

Optimal formal decision-making is based on realistic behaviour of actors, important in land–climate systems, assessed through participatory approaches, stakeholder consultations and by incorporating results from empirical analyses. Mathematical simulations and games (Lamarque et al. 2013), behavioural models in land-based sectors (Brown et al. 2017), agent-based models and micro-simulations are examples useful to decision-makers (Bishop et al. 2013). These decision-making tools are expanded on in Section 7.5.2.

There are different ways to incorporate local knowledge, informal institutions and other contextual characteristics that capture non-deterministic elements, as well as social and cultural beliefs and systems more generally, into formal decision-making (*medium evidence*, *medium agreement*) (Section 7.6.4). Classic scientific methodologies now include participatory and interdisciplinary methods and approaches (Jones et al. 2014). Consequently, this broader range of approaches may capture informal and indigenous knowledge, improving the participation of indigenous peoples in decision-making processes, and thereby promote their rights to self-determination (Malogdos and Yujuico 2015b) (Cross-Chapter Box 13 in Chapter 7).

7.5.1.2 Informal decision-making

Informal institutions have contributed to sustainable resources management (common pool resources) through creating a suitable environment for decision-making. The role of informal institutions indecision-making can be particularly relevant for land-use decisions and practices in rural areas in the global south and north (Huisheng 2015). Understanding informal institutions is crucial for adapting to climate change, advancing technological adaptation measures, achieving comprehensive disaster management and advancing collective decision-making (Karim and Thiel 2017). Informal institutions have been found to be a crucial entry point in dealing with vulnerability of communities and exclusionary tendencies impacting on marginalised and vulnerable people (Mubaya and Mafongoya 2017).

Many studies underline the role of local/informal traditional institutions in the management of natural resources in different parts of the world (Yami et al. 2009; Zoogah et al. 2015; Bratton 2007; Mowo et al. 2013; Grzymala-Busse 2010). Traditional systems include: traditional silvopastoral management (Iran), management of rangeland resources (South Africa), natural resource management (Ethiopia, Tanzania, Bangladesh) communal grazing land management (Ethiopia) and management of conflict over natural resources (Siddig et al. 2007; Yami et al. 2011; Valipour et al. 2014; Bennett 2013; Mowo et al. 2013).

Formal–informal institutional interaction could take different shapes such as: complementary, accommodating, competing, and substitutive. There are many examples when formal institutions might obstruct, change, and hinder informal institutions (Rahman et al. 2014; Helmke and Levitsky 2004; Bennett 2013; Osei-Tutu et al. 2014). Similarly, informal institutions can replace, undermine, and reinforce formal institutions (Grzymala-Busse 2010). In the absence of formal institutions, informal institutions gain importance, requiring focus in relation to natural resources management and rights protection (Estrin and Prevezer 2011; Helmke and Levitsky 2004; Kangalawe et al. 2014; Sauerwald and Peng 2013; Zoogah et al. 2015).

Community forestry comprises 22% of forests in tropical countries in contrast to large-scale industrial forestry (Hajjar et al. 2013) and is managed with informal institutions, ensuring a sustainable flow of forest products and income, utilising traditional ecological knowledge to determine access to resources (Singh et al. 2018). Policies that create an open platform for local debates and allow actors their own active formulation of rules strengthen informal institutions. Case studies in Zambia, Mali, Indonesia and Bolivia confirm that enabling factors for advancing the local ownership of resources and crafting durability of informal rules require recognition in laws, regulations and policies of the state (Haller et al. 2016).

7.5.2 Decision-making, timing, risk, and uncertainty

This section assesses decision-making literature, concluding that advances in methods have been made in the face of conceptual risk literature and, together with a synthesis of empirical evidence, near-term decisions have significant impact on costs.

7.5.2.1 Problem structuring

Structured decision-making occurs when there is scientific knowledge about cause and effect, little uncertainty, and agreement exists on values and norms relating to an issue (Hurlbert and Gupta 2016). This decision space is situated within the 'known' space where cause and effect is understood and predictable (although uncertainty is not quite zero) (French 2015). Figure 7.5 displays the structured problem area in the bottom left-hand corner corresponding with the 'known' decision-making space. Decision-making surrounding quantified risk assessment and risk management (Section 7.4.3.1) occurs within this decision-making space. Examples in the land and climate area include cost-benefit analysis surrounding implementation of irrigation projects (Batie 2008) or adopting soil erosion practices by agricultural producers based on anticipated profit (Hurlbert 2018b). Comprehensive risk management also occupies this decision space (Papathoma-Köhle et al. 2016), encompassing risk assessment, reduction, transfer, retention, emergency preparedness and response, and disaster recovery by combining quantified proactive and reactive approaches (Fra.Paleo 2015) (Section 7.4.3).

A moderately structured decision space is characterised as one where there is either some disagreement on norms, principles, ends and goals in defining a future state, or there is some uncertainty surrounding land and climate including land use, observations of land-use changes, early warning and decision support systems, model structures, parameterisations, inputs, or from unknown futures informing integrated assessment models and scenarios (see Chapter 1, Section 1.2.2 and Cross-Chapter Box 1 in Chapter 1). Environmental decision-making often takes place in this space where there is limited information and ability to process it, and individual stakeholders make different decisions on the best future course of action (*medium confidence*) (Waas et al. 2014; Hurlbert and Gupta 2016, 2015; Hurlbert 2018b). Figure 7.5 displays the moderately structured problem space characterised by disagreement surrounding norms on the top left-hand side. This corresponds with the complex decision-making space, the realm of social sciences and qualitative knowledge, where cause and effect is difficult to relate with any confidence (French 2013).

The moderately structured decision space characterised by uncertainty surrounding land and climate on the bottom right-hand side of Figure 7.5 corresponds to the knowable decision-making space, where the realm of scientific inquiry investigates cause and effects. Here there is sufficient understanding to build models, but not enough understanding to define all parameters (French 2015).

The top right-hand corner of Figure 7.5 corresponds to the 'unstructured' problem or chaotic space where patterns and relationships are difficult to discern and unknown unknowns reside (French 2013). It is in the complex but knowable space, the structured and moderately structured space, that decision-making under uncertainty occurs.

7.5.2.2 Decision-making tools

Decisions can be made despite uncertainty (*medium confidence*), and a wide range of possible approaches are emerging to support decision-making under uncertainty (Jones et al. 2014), applied both to adaptation and mitigation decisions.

Traditional approaches for economic appraisal, including cost-benefit analysis and cost-effectiveness analysis referred to in Section 7.5.2.1 do not handle or address uncertainty well (Hallegatte 2009; Farber 2015) and favour decisions with short-term benefits (see Cross-Chapter Box 10 in this chapter). Alternative economic decision-making approaches aim to better incorporate uncertainty while delivering adaptation goals, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al. 2012) – so-called 'robust' decision-making approaches. These are designed to be less sensitive to uncertainty about the future (Lempert and Schlesinger 2000).

Much of the research for adaptation to climate change has focused around three main economic approaches: real options analysis, portfolio analysis, and robust decision-making. Real options analysis develops flexible strategies that can be adjusted when additional climate information becomes available. It is most appropriate for large irreversible investment decisions. Applications to climate adaptation are growing quickly, with most studies addressing flood risk and sea-level rise (Gersonius et al. 2013; Woodward et al. 2014; Dan 2016), but studies in land-use decisions are also emerging, including identifying the optimal time to switch land use in a changing climate (Sanderson et al. 2016) and water storage (Sturm et al. 2017; Kim et al. 2017). Portfolio analysis aims to reduce risk by diversification, by planting multiple species rather than only one, for example, in forestry (Knoke et al. 2017) or crops (Ben-Ari and Makowski 2016), or in multiple locations. There may be a trade-off between robustness to variability and optimality (Yousefpour and Hanewinkel 2016; Ben-Ari and Makowski 2016); but this type of analysis can help identify and quantify trade-offs. Robust decision-making identifies how different strategies perform under many climate outcomes, also potentially trading off optimality for resilience (Lempert 2013).

Multi-criteria decision-making continues to be an important tool in the land-use sector, with the capacity to simultaneously consider multiple goals across different domains (e.g., economic, environmental, social) (Bausch et al. 2014; Alrø et al. 2016), and so is useful as a mitigation as well as an adaptation tool. Lifecycle assessment can also be used to evaluate emissions across a system – for example, in livestock production (McClelland et al. 2018) – and to identify areas to prioritise for reductions. Bottom-up marginal abatement cost curves calculate the most cost effective cumulative potential for mitigation across different options (Eory et al. 2018).

In the climate adaptation literature, these tools may be used in adaptive management (Section 7.5.4), using a monitoring, research, evaluation and learning process (cycle) to improve future management strategies (Tompkins and Adger 2004). More recently these techniques have been advanced with iterative risk management (IPCC 2014a) (Sections 7.4.1 and 7.4.7), adaptation pathways (Downing 2012), and dynamic adaptation pathways (Haasnoot et al. 2013) (Section 7.6.3). Decision-making tools can be selected and adapted to fit the specific land and climate problem and decision-making space. For instance, dynamic adaptation pathways processes (Haasnoot et al. 2013; Wise et al. 2014) identify and sequence potential actions based on alternative potential futures and are situated within the complex, unstructured space (see Figure 7.5). Decisions are made based on trigger points, linked to indicators and scenarios, or changing performance over time (Kwakkel et al. 2016). A key characteristic of these pathways is that, rather than making irreversible decisions now, decisions evolve over time, accounting for learning (Section 7.6.4), knowledge, and values. In New Zealand, combining dynamic adaptive pathways and a form of real options analysis with multiple-criteria decision analysis has enabled risk that changes over time to be included in the assessment of adaptation options through a participatory learning process (Lawrence et al. 2019).

Scenario analysis is also situated within the complex, unstructured space (although, unlike adaptation pathways, it does not allow for changes in pathway over time) and is important for identifying technology and policy instruments to ensure spatial-temporal coherence of land-use allocation simulations with scenario storylines (Brown and Castellazzi 2014) and identifying technology and policy instruments for mitigation of land degradation (Fleskens et al. 2014).

While economics is usually based on the idea of a self-interested, rational agent, more recently insights from psychology are being used to understand and explain human behaviour in the field of behavioural economics (Shogren and Taylor 2008; Kesternich et al. 2017), illustrating how a range of cognitive factors and biases can affect choices (Valatin et al. 2016). These insights can be critical in supporting decision-making that will lead to more desirable outcomes relating to land and climate change. One example of this is 'policy nudges' (Thaler and Sunstein 2008) which can 'shift choices in socially desirable directions' (Valatin et al. 2016). Tools can include framing tools, binding pre-commitments, default settings, channel factors, or broad choice bracketing (Wilson et al. 2016). Although relatively few empirical examples exist in the land sector, there is evidence that nudges could be applied successfully, for example, in woodland creation (Valatin et al. 2016) and agri-environmental schemes (Kuhfuss et al. 2016) (*medium certainty*, *low evidence*). Consumers can be 'nudged' to consume less meat (Rozin et al. 2011) or to waste less food (Kallbekken and Sælen 2013).

Programmes supporting and facilitating desired practices can have success at changing behaviour, particularly if they are co-designed by the end-users (farmers, foresters, land users) (*medium evidence*, *high agreement*). Programmes that focus on demonstration or trials of different adaptation and mitigation measures, and facilitate interaction between farmers and industry specialists are perceived as being successful (Wreford et al. 2017; Hurlbert 2015b) but systematic evaluations of their success at changing behaviour are limited (Knook et al. 2018).

Different approaches to decision-making are appropriate in different contexts. Dittrich et al. (2017) provide a guide to the appropriate application in different contexts for adaptation in the livestock sector in developed countries. While considerable advances have been made in theoretical approaches, a number of challenges arise when applying these in practice, and partly relate to the necessity of assigning probabilities to climate projects, and the complexity of the approaches being a prohibitive factor beyond academic exercises. Formalised expert judgement can improve how uncertainty is characterised (Kunreuther et al. 2014) and these methods have been improved utilising Bayesian belief networks to synthesise expert judgements and include fault trees and reliability block diagrams to overcome standard reliability techniques (Sigurdsson et al. 2001) as well as mechanisms incorporating transparency (Ashcroft et al. 2016).

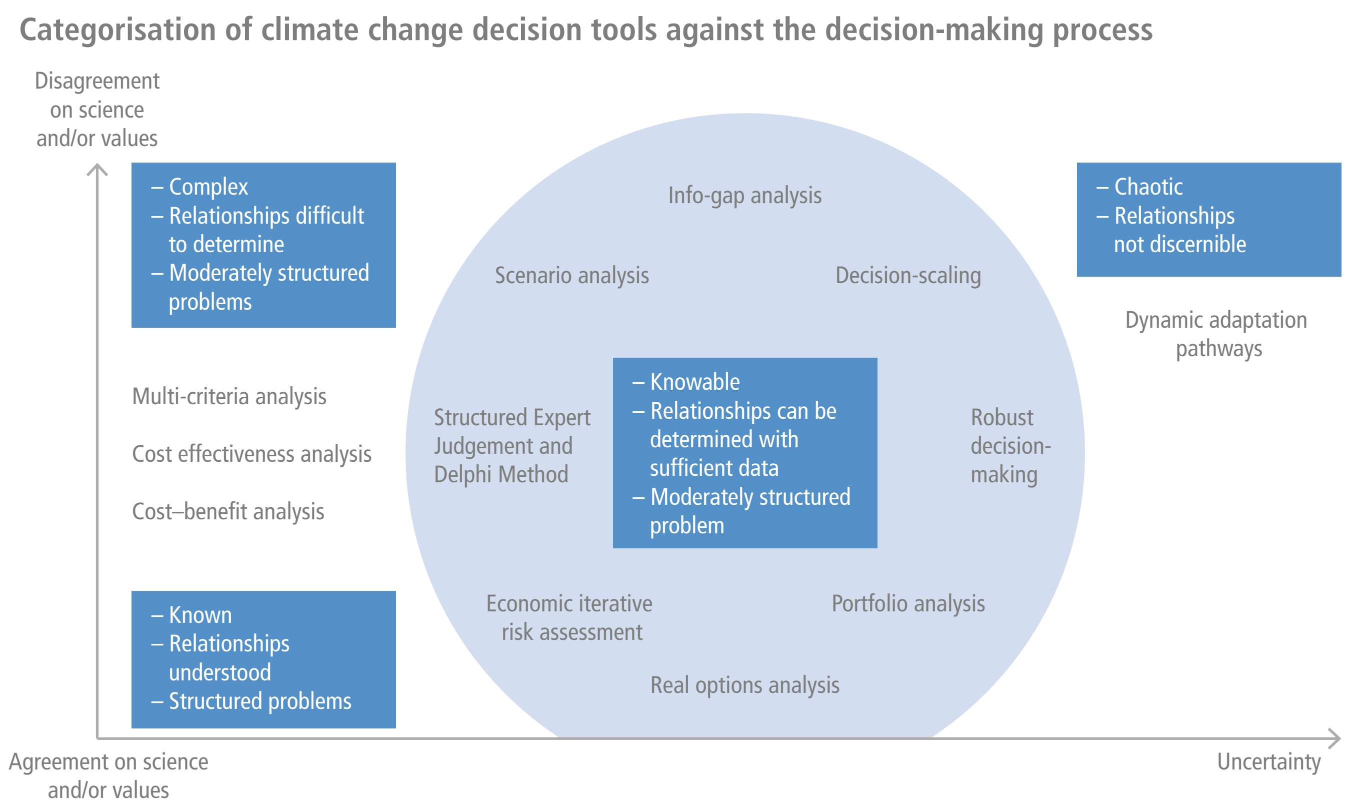

Figure 7.5 | Structural and uncertain decision making.

It may also be beneficial to combine decision-making approaches with the precautionary principle, or the idea that lack of scientific certainty is not to postpone action when faced with serious threats or irreversible damage to the environment (Farber 2015). The precautionary principle requires cost-effective measures to address serious but uncertain risks (Farber 2015). It supports a rights-based policy instrument choice as consideration is whether actions or inactions harm others moving beyond traditional risk-management policy considerations that surround net benefits (Etkin et al. 2012). Farber, (2015) concludes that the principle has been successfully applied in relation to endangered species and situations where climate change is a serious enough problem to justify some response. There is *medium confidence* that combining the precautionary principle with integrated assessment models, risk management, and cost-benefit analysis in an integrated, holistic manner, would be a good combination of decision-making tools supporting sustainable development (Farber 2015; Etkin et al. 2012).

7.5.2.3 Cost and timing of action

The Cross-Chapter Box 10 on Economic dimensions of climate change and land deals with the costs and timing of action. In terms of policies, not only is timing important, but the type of intervention itself can influence returns (*high evidence*, *high agreement*). Policy packages that make people more resilient – expanding financial inclusion, disaster risk and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems (Sections 7.4.1 and 7.6.3) – could save 100 billion USD a year, if implemented globally (Hallegatte et al. 2017). In Ethiopia, Kenya and Somalia, every 1 USD spent on safety-net/resilience programming results in net benefits of between 2.3 and 3.3 USD (Venton 2018). Investing in resilience-building activities, which increase household income by 365 to 450 USD per year in these countries, is more cost effective than providing ongoing humanitarian assistance.

There is a need to further examine returns on investment for land-based adaptation measures, both in the short and long term. Other outstanding questions include identifying specific triggers for early response. Food insecurity, for example, can occur due to a mixture of market and environmental factors (changes in food prices, animal or crop prices, rainfall patterns) (Venton 2018). The efficacy of different triggers, intervention times and modes of funding are currently being evaluated (see, for example, forecast-based finance study; Alverson and Zommers 2018). To reduce losses and maximise returns on investment, this information can be used to develop: 1) coordinated, agreed plans for action; 2) a clear, evidence-based decision-making process, and; 3) financing models to ensure that the plans for early action can be implemented (Clarke and Dercon 2016a).

7.5.3 Best practices of decision-making toward sustainable land management (SLM)

Sustainable land management (SLM) is a strategy and also an outcome (Waas et al. 2014) and decision-making practices are fundamental in achieving it as an outcome (*medium evidence*, *medium agreement*). SLM decision-making is improved (*medium evidence* and *high agreement*) with ecological service mapping with three characteristics: robustness (robust modelling, measurement, and stakeholder-based methods for quantification of ES supply, demand and/or flow, as well as measures of uncertainty and heterogeneity across spatial and temporal scales and resolution); transparency (to contribute to clear information-sharing and the creation of linkages with decision support processes); and relevancy to stakeholders (people-centric in which stakeholders are engaged at different stages) (Willemen et al. 2015; Ashcroft et al. 2016). Practices that advance SLM include remediation practices, as well as critical interventions that are reshaping norms and standards, joint implementation, experimentation, and integration of rural actors' agency in analysis and approaches in decision-making (Hou and Al-Tabbaa 2014). Best practices are identified in the literature after their implementation demonstrates effectiveness at improving water quality, the environment, or reducing pollution (Rudolph et al. 2015; Lam et al. 2011).

There is *medium evidence* and *medium agreement* about what factors consistently determine the adoption of agricultural best management practices (Herendeen and Glazier 2009) and these positively correlate to education levels, income, farm size, capital, diversity, access to information, and social networks. Attending workshops for information and trust in crop consultants are also important factors in adoption of best management practices (Ulrich-Schad et al. 2017; Baumgart-Getz et al. 2012). More research is needed on the sustained adoption of these factors over time (Prokopy et al. 2008).

There is *medium evidence* and *high agreement* that SLM practices and incentives require mainstreaming into relevant policy; appropriate market-based approaches, including payment for ES and public-private partnerships, need better integration into payment schemes (Tengberg et al. 2016). There is *medium evidence* and *high agreement* that many of the best SLM decisions are made with the participation of stakeholders and social learning (Section 7.6.4) (Stringer and Dougill 2013). As stakeholders may not be in agreement, either practices of mediating agreement, or modelling that depicts and mediates the effects of stakeholder perceptions in decision-making may be applicable (Hou 2016; Wiggering and Steinhardt 2015).

7.5.4 Adaptive management

Adaptive management is an evolving approach to natural resource management founded on decision-making approaches in other fields (such as business, experimental science, and industrial ecology) (Allen et al. 2011; Williams 2011) and decision-making that overcomes management paralysis and mediates multiple stakeholder interests through use of simple steps. Adaptive governance considers a broader socio-ecological system that includes the social context that facilitates adaptive management (Chaffin et al. 2014). Adaptive management steps include evaluating a problem and integrating planning, analysis and management into a transparent process to build a road map focused on achieving fundamental objectives. Requirements of success are clearly articulated objectives, the explicit acknowledgment of uncertainty, and a transparent response to all stakeholder interests in the decision-making process (Allen et al. 2011). Adaptive management builds on this foundation by incorporating a formal iterative process, acknowledging uncertainty and achieving management objectives through a structured feedback process that includes stakeholder participation (Foxon et al. 2009) (Section 7.6.4). In the adaptive management process, the problem and desired goals are identified, evaluation criteria formulated, the system boundaries and context are ascertained, trade-offs evaluated, decisions are made regarding responses and policy instruments, which are implemented, and monitored, evaluated and adjusted (Allen et al. 2011). The implementation of policy strategies and monitoring of results occurs in a continuous management cycle of monitoring, assessment and revision (Hurlbert 2015b; Newig et al. 2010; Pahl-Wostl et al. 2007), as illustrated in Figure 7.6.

A key focus on adaptive management is the identification and reduction of uncertainty (as described in Chapter 1, Section 1.2.2 and Cross-Chapter Box 1 on Scenarios) and partial controllability, whereby policies used to implement an action are only indirectly responsible (for example, setting a harvest rate) (Williams 2011). There is *medium evidence* and *high agreement* that adaptive management is an ideal method to resolve uncertainty when uncertainty and controllability (resources will respond to management) are both high (Allen et al. 2011). Where uncertainty is high, but controllability is low, developing and analysing scenarios may be more appropriate (Allen et al. 2011). Anticipatory governance has developed combining scenarios and forecasting in order to creatively design strategy to address 'complex, fuzzy and wicked challenges' (Ramos 2014; Quay 2010) (Section 7.5). Even where there is low controllability, such as in the case of climate change, adaptive management can help mitigate impacts, including changes in water availability and shifting distributions of plants and animals (Allen et al. 2011).

There is *medium evidence* and *high agreement* that adaptive management can help reduce anthropogenic impacts of changes of land and climate, including: species decline and habitat loss (participative identification, monitoring, and review of species at risk as well as decision-making surrounding protective measures) (Fontaine 2011; Smith 2011) including quantity and timing of harvest of animals (Johnson 2011a), human participation in natural resource-based recreational activities, including selection fish harvest quotas and fishing seasons from year to year (Martin and Pope 2011), managing competing interests of land-use planners and conservationists in public lands (Moore et al. 2011), managing endangered species and minimising fire risk through land-cover management (Breininger et al. 2014), land-use change in hardwood forestry through mediation of hardwood plantation forestry companies and other stakeholders, including those interested in water, environment or farming (Leys and Vanclay 2011), and SLM protecting biodiversity, increasing carbon storage, and improving livelihoods (Cowie et al. 2011). There is *medium evidence* and *medium agreement* that, despite abundant literature and theoretical explanation, there has remained imperfect realisation of adaptive management because of several challenges: lack of clarity in definition and approach, few success stories on which to build an experiential base practitioner knowledge of adaptive management, paradigms surrounding management, policy and funding that favour reactive approaches instead of the proactive adaptive management approach, shifting objectives that do not allow for the application of the approach, and failure to acknowledge social uncertainty (Allen et al. 2011). Adaptive management includes participation (Section 7.6.4), the use of indicators (Section 7.5.5), in order to avoid maladaptation and trade-offs while maximising synergies (Section 7.5.6).

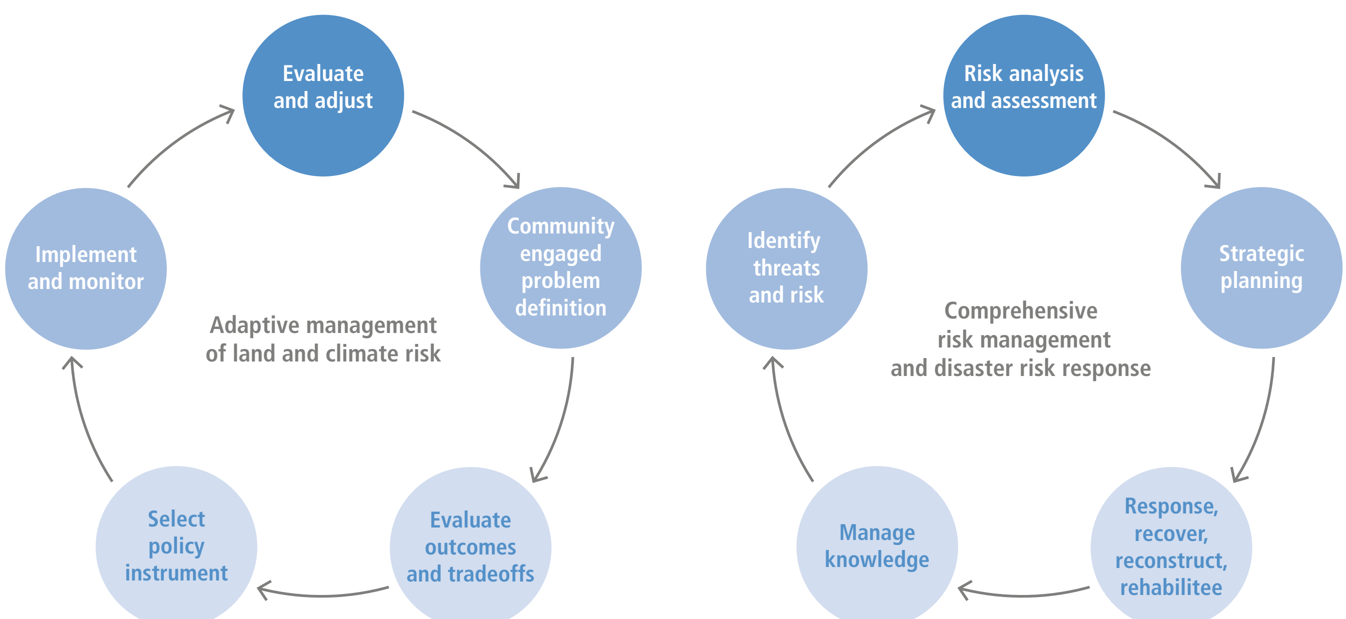

Figure 7.6 | Adaptive governance, management and comprehensive iterative risk management. Source: Adapted from Ammann 2013; Allen et al. 2011.

7.5.5 Performance indicators

Measuring performance is important in adaptive management decision-making, policy instrument implementation and governance, and can help evaluate policy effectiveness (*medium evidence*, *high agreement*) (Wheaton and Kulshreshtha 2017; Bennett and Dearden 2014; Oliveira Júnior et al. 2016; Kaufmann 2009). Indicators can relate to specific policy problems (climate mitigation, land degradation), sectors (agriculture, transportation, etc.), and policy goals (SDGs, food security).

It is necessary to monitor and evaluate the effectiveness and efficiency of performing climate actions to ensure the long-term success of climate initiatives or plans. Measurable indicators are useful for climate policy development and decision-making processes since they can provide quantifiable information regarding the progress of climate actions. The Paris Agreement (UNFCCC 2015) focused on reporting the progress of implementing countries' pledges – that is, NDCs and national adaptation needs in order to examine the aggregated results of mitigation actions that have already been implemented. For the case of measuring progress toward achieving LDN, it was suggested to use land-based indicators – that is, trends in land cover and land productivity or functioning of the land, and trends in carbon stock above and below ground (Cowie et al. 2018a). There is *medium evidence* and *high agreement* that indicators for measuring biodiversity and ES in response to governance at local to international scales meet the criteria of parsimony and scale specificity, are linked to some broad social, scientific and political consensus on desirable states of ecosystems and biodiversity, and include normative aspects such as environmental justice or socially just conservation (Layke 2009; Van Oudenhoven et al. 2012; Turnhout et al. 2014; Häyhä and Franzese 2014; Guerry et al. 2015; Díaz et al. 2015).

Important in making choices of metrics and indicators is understanding that the science, linkages and dynamics in systems are complex, not amenable to be addressed by simple economic instruments, and are often unrelated to short-term management or governance scales (Naeem et al. 2015; Muradian and Rival 2012). Thus, ideally, stakeholders participate in the selection and use of indicators for biodiversity and ES and monitoring impacts of governance and management regimes on land–climate interfaces. The adoption of non-economic approaches that are part of the emerging concept of Nature's Contributions to People (NCP) could potentially elicit support for conservation from diverse sections of civil society (Pascual et al. 2017).

Recent studies increasingly incorporate the role of stakeholders and decision-makers in the selection of indicators for land systems (Verburg et al. 2015) including sustainable agriculture (Kanter et al. 2016), bioenergy sustainability (Dale et al. 2015), desertification (Liniger et al. 2019), and vulnerability (Debortoli et al. 2018). Kanter et al. (2016) propose a four-step 'cradle-to-grave' approach for agriculture trade-off analysis, which involves co-evaluation of indicators and trade-offs with both stakeholders and decision-makers.

7.5.6 Maximising synergies and minimising trade-offs

Synergies and trade-offs to address land and climate-related measures are identified and discussed in Chapter 6. Here we outline policies supporting Chapter 6 response options (see Table 7.5), and discuss synergies and trade-offs in policy choices and interactions among policies. Trade-offs will exist between broad policy approaches. For example, while legislative and regulatory approaches may be effective at achieving environmental goals, they may be costly and ideologically unattractive in some countries. Market-driven approaches such as carbon pricing are cost-effective ways to reduce emissions, but may not be favoured politically and economically (Section 7.4.4). Information provision involves little political risk or ideological constraints, but behavioural barriers may limit their effectiveness (Henstra 2016). This level of trade-off is often determined by the prevailing political system.

Synergies and trade-offs also result from interaction between policies (policy interplay; Urwin and Jordan 2008) at different levels of policy (vertical) and across different policies (horizontal) (Section 7.4.8). If policy mixes are designed appropriately, acknowledging and incorporating trade-offs and synergies, they are better placed to deliver an outcome such as transitioning to sustainability (Howlett and Rayner 2013; Huttunen et al. 2014) (*medium evidence* and *medium agreement*). However, there is *limited evidence* and *medium agreement* that evaluating policies for coherence in responding to climate change and its impacts is not occurring, and policies are instead reviewed in a fragmented manner (Hurlbert and Gupta 2016).

Table 7.5 | Selection of policies/programmes/instruments that support response options.

Category	Integrated response option	Policy instrument supporting response option
Land management in agriculture	Increased food productivity	Investment in agricultural research for crop and livestock improvement, agricultural technology transfer, inland capture fisheries and aquaculture {7.4.7} agricultural policy reform and trade liberalisation
	Improved cropland, grazing, and livestock management	Environmental farm programmes/agri-environment schemes, water-efficiency requirements and water transfer {3.7.5}, extension services
	Agroforestry	Payment for ecosystem services (ES) {7.4.6}
	Agricultural diversification	Elimination of agriculture subsidies {5.7.1}, environmental farm programmes, agri-environmental payments {7.4.6}, rural development programmes
	Reduced grassland conversion to cropland	Elimination of agriculture subsidies, remove insurance incentives, ecological restoration {7.4.6}
	Integrated water management	Integrated governance {7.6.2}, multi-level instruments {7.4.1}
Land management in forests	Forest management, reduced deforestation and degradation, reforestation and forest restoration, afforestation	REDD+, forest conservation regulations, payments for ES, recognition of forest rights and land tenure {7.4.6}, adaptive management of forests {7.5.4}, land-use moratoriums, reforestation programmes and investment {4.9.1}
Land management of soils	Increased soil organic carbon content, reduced soil erosion, reduced soil salinisation, reduced soil compaction, biochar addition to soil	Land degradation neutrality (LDN) {7.4.5}, drought plans, flood plans, flood zone mapping {7.4.3}, technology transfer (7.4.4}, land-use zoning {7.4.6}, ecological service mapping and stakeholder-based quantification {7.5.3}, environmental farm programmes/agri-environment schemes, water-efficiency requirements and water transfer {3.7.5}
Land management in all other ecosystems	Fire management	Fire suppression, prescribed fire management, mechanical treatments {7.4.3}
	Reduced landslides and natural hazards	Land-use zoning {7.4.6}
	Reduced pollution – acidification	Environmental regulations, climate mitigation (carbon pricing) {7.4.4}
	Management of invasive species/ encroachment	Invasive species regulations, trade regulations {5.7.2, 7.4.6}
	Restoration and reduced conversion of coastal wetlands	Flood zone mapping {7.4.3}, land-use zoning {7.4.6}
	Restoration and reduced conversion of peatlands	Payment for ES {7.4.6; 7.5.3}, standards and certification programmes {7.4.6}, land-use moratoriums
	Biodiversity conservation	Conservation regulations, protected areas policies
Carbon dioxide removal (CDR) land management	Enhanced weathering of minerals	No data
	Bioenergy and bioenergy with carbon capture and storage (BECCS)	Standards and certification for sustainability of biomass and land use {7.4.6}
Demand management	Dietary change	Awareness campaigns/education, changing food choices through nudges, synergies with health insurance and policy {5.7.2}
	Reduced post-harvest losses Reduced food waste (consumer or retailer), material substitution	Agricultural business risk programmes {7.4.8}; regulations to reduce and taxes on food waste, improved shelf life, circularising the economy to produce substitute goods, carbon pricing, sugar/fat taxes {5.7.2}
Supply management	Sustainable sourcing	Food labelling, innovation to switch to food with lower environmental footprint, public procurement policies {5.7.2}, standards and certification programmes {7.4.6}
	Management of supply chains	Liberalised international trade {5.7.2}, food purchasing and storage policies of governments, standards and certification programmes {7.4.6}, regulations on speculation in food systems
	Enhanced urban food systems	Buy local policies; land-use zoning to encourage urban agriculture, nature-based solutions and green infrastructure in cities; incentives for technologies like vertical farming
	Improved food processing and retailing, improved energy use in food systems	Agriculture emission trading {7.4.4}; investment in R&D for new technologies; certification
Risk management	Management of urban sprawl	Land-use zoning {7.4.6}
	Livelihood diversification	Climate-smart agriculture policies, adaptation policies, extension services {7.5.6}
	Disaster risk management	Disaster risk reduction {7.5.4; 7.4.3}, adaptation planning
	Risk-sharing instruments	Insurance, iterative risk management, CAT bonds, risk layering, contingency funds {7.4.3}, agriculture business risk portfolios {7.4.8}

Cross-Chapter Box 9 | Climate and land pathways

This is a duplicate of Cross-Chapter Box 9 in Chapter 6.

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Future development of socio-economic factors and policies influence the evolution of the land–climate system, among others, in terms of the land used for agriculture and forestry. Climate mitigation policies can also have a major impact on land use, especially in scenarios consistent with the climate targets of the Paris Agreement. This includes the use of bio-energy or CDR, such as bioenergy with carbon capture and storage (BECCS) and afforestation. Land-based mitigation options have implications for GHG fluxes, desertification, land degradation, food insecurity, ecosystem services and other aspects of sustainable development.

Shared Socio-economic Pathways

The five pathways are based on the Shared Socio-economic Pathways (SSPs) (O'Neill et al. 2014; Popp et al. 2017; Riahi et al. 2017; Rogelj et al. 2018b) (Cross-Chapter Box 1 in Chapter 1). SSP1 is a scenario with a broad focus on sustainability, including human development, technological development, nature conservation, globalised economy, economic convergence and early international cooperation (including moderate levels of trade). The scenario includes a peak and decline in population, relatively high agricultural yields and a move towards food produced in low-GHG emission systems (Van Vuuren et al. 2017b). Dietary change and reductions in food waste reduce agricultural demands, and effective land-use regulation enables reforestation and/or afforestation. SSP2 is a scenario in which production and consumption patterns, as well as technological development, follows historical patterns (Fricko et al. 2017). Land-based CDR is achieved through bioenergy and BECCS and, to a lesser degree, by afforestation and reforestation. SSP3 is a scenario with slow rates of technological change and limited land-use regulation. Agricultural demands are high due to material-intensive consumption and production, and barriers to trade lead to reduced flows for agricultural goods. In SSP3, forest mitigation activities and abatement of agricultural GHG emissions are limited due to major implementation barriers such as low institutional capacities in developing countries and delays as a consequence of low international cooperation (Fujimori et al. 2017). Emissions reductions are achieved primarily through the energy sector, including the use of bioenergy and BECCS.

Policies in the Pathways

SSPs are complemented by a set of shared policy assumptions (Kriegler et al. 2014), indicating the types of policies that may be implemented in each future world. Integrated Assessment Models (IAMs) represent the effect of these policies on the economy, energy system, land use and climate with the caveat that they are assumed to be effective or, in some cases, the policy goals (e.g., dietary change) are imposed rather than explicitly modelled. In the real world, there are various barriers that can make policy implementation more difficult (Section 7.4.9). These barriers will be generally higher in SSP3 than SSP1.

SSP1: A number of policies could support SSP1 in future, including: effective carbon pricing, emission trading schemes (including net CO_2 emissions from agriculture), carbon taxes, regulations limiting GHG emissions and air pollution, forest conservation (mix of land sharing and land sparing) through participation, incentives for ecosystem services and secure tenure, and protecting the environment, microfinance, crop and livelihood insurance, agriculture extension services, agricultural production subsidies, low export tax and import tariff rates on agricultural goods, dietary awareness campaigns, taxes on and regulations to reduce food waste, improved shelf life, sugar/fat taxes, and instruments supporting sustainable land management, including payment for ecosystem services, land-use zoning, REDD+, standards and certification for sustainable biomass production practices, legal reforms on land ownership and access, legal aid, legal education, including reframing these policies as entitlements for women and small agricultural producers (rather than sustainability) (Van Vuuren et al. 2017b; O'Neill et al. 2017) (Section 7.4).

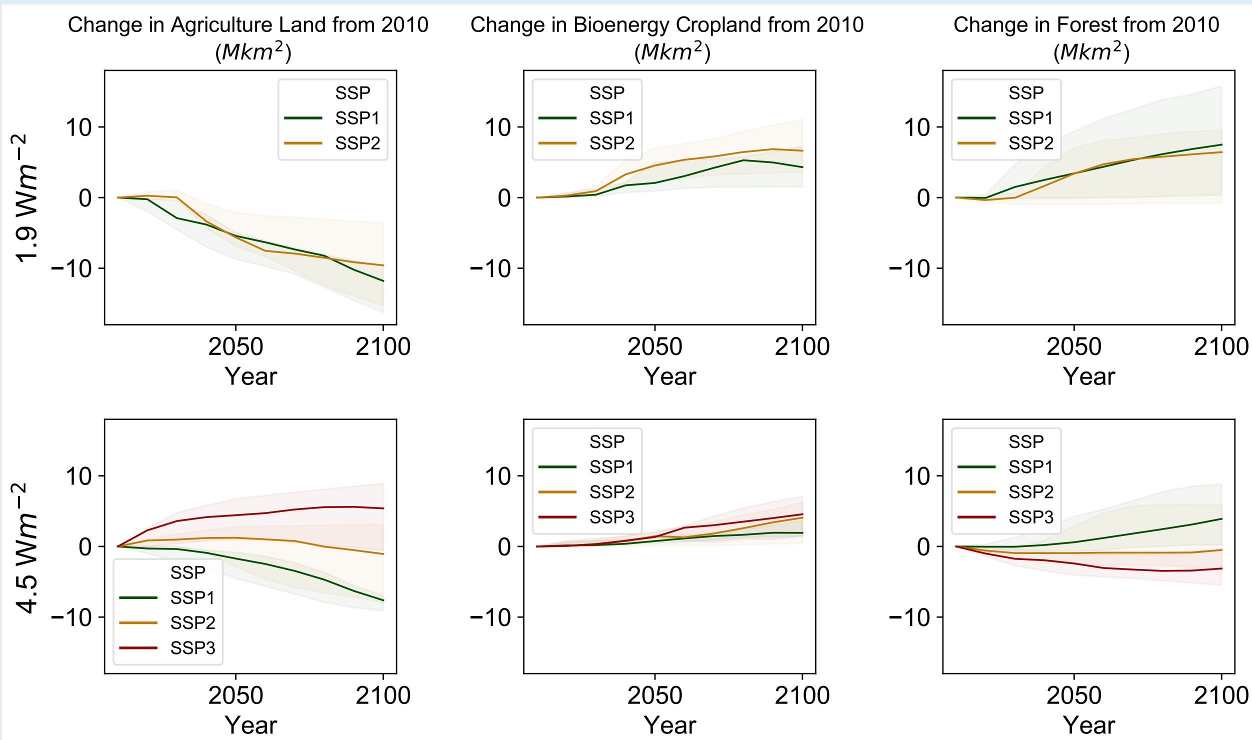
SSP2: The same policies that support SSP1 could support SSP2 but may be less effective and only moderately successful. Policies may be challenged by adaptation limits (Section 7.4.9), inconsistency in formal and informal institutions in decision-making (Section 7.5.1) or result in maladaptation (Section 7.4.7). Moderately successful sustainable land management policies result in some land competition. Land degradation neutrality is moderately successful. Successful policies include those supporting bioenergy and BECCS (Rao et al. 2017b; Fricko et al. 2017; Riahi et al. 2017) (Section 7.4.6).

SSP3: Policies that exist in SSP1 may or may not exist in SSP3, and are ineffective (O'Neill et al. 2014). There are challenges to implementing these policies, as in SSP2. In addition, ineffective sustainable land management policies result in competition for land between agriculture and mitigation. Land degradation neutrality is not achieved (Riahi et al. 2017). Successful policies include those supporting bioenergy and BECCS (Kriegler et al. 2017; Fujimori et al. 2017; Rao et al. 2017b) (Section 7.4.6). Demand-side food policies are absent and supply-side policies predominate. There is no success in advancing land ownership and access policies for agricultural producer livelihood (Section 7.6.5).

Cross-Chapter Box 9 (continued)

Land-use and land-cover change

In SSP1, sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation and bioenergy. In contrast, SSP3 has high population and strongly declining rates of crop yield growth over time, resulting in increased agricultural land area. SSP2 falls somewhere in between, with societal as well as technological development following historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre. In the climate policy scenarios consistent with the Paris Agreement, bioenergy/BECCS and reforestation/afforestation play an important role in SSP1 and SSP2. The use of these options, and the impact on land, is larger in scenarios that limit radiative forcing in 2100 to 1.9 W m^{-2} than in the 4.5 W m^{-2} scenarios. In SSP3, the expansion of land for agricultural production implies that the use of land-related mitigation options is very limited, and the scenario is characterised by continued deforestation.



Cross-Chapter Box 9, Figure 1 | Changes in agriculture land (left), bioenergy cropland (middle) and forest (right) under three different SSPs (colours) and two different warming levels (rows). Agricultural land includes both pasture and cropland. Colours indicate SSPs, with SSP1 shown in green, SSP2 in yellow, and SSP3 in red. For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. There is no SSP3 in the top row, as 1.9 W m^{-2} is infeasible in this world. Data is from an update of the Integrated Assessment Modelling Consortium (IAMC) Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018a).

Implications for mitigation and other land challenges

The combination of baseline emissions development, technology options, and policy support makes it much easier to reach the climate targets in the SSP1 scenario than in the SSP3 scenario. As a result, carbon prices are much higher in SSP3 than in SSP1. In fact, the 1.9 W m^{-2} target was found to be infeasible in the SSP3 world (Table 1 in Cross-Chapter Box 9). Energy system CO_2 emissions reductions are greater in SSP3 than in SSP1 to compensate for the higher land-based CO_2 emissions.

Accounting for mitigation and socio-economics alone, food prices (an indicator of food insecurity) are higher in SSP3 than in SSP1 and higher in the 1.9 W m^{-2} target than in the 4.5 W m^{-2} target (Table 1 in Cross-Chapter Box 9). Forest cover is higher in SSP1 than SSP3 and higher in the 1.9 W m^{-2} target than in the 4.5 W m^{-2} target. Water withdrawals and water scarcity are, in general, higher in SSP3 than SSP1 (Hanasaki et al. 2013; Graham et al. 2018) and higher in scenarios with more bioenergy (Hejazi et al. 2014b); however, these indicators have not been quantified for the specific SSP-representative concentration pathways (RCP) combinations discussed here.

Cross-Chapter Box 9 (continued)

Cross-Chapter Box 9, Table 1 | Quantitative indicators for the pathways. Each cell shows the mean, minimum, and maximum value across IAM models for each indicator and each pathway in 2050 and 2100. All IAMs that provided results for a particular pathway are included here. Note that these indicators exclude the implications of climate change. Data is from an update of the IAMC Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018b).

		SSP1		SSP2		SSP3	
		1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)	1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)	1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)
Population (billion)	2050	8.5 (8.5, 8.5)	8.5 (8.5, 8.5)	9.2 (9.2, 9.2)	9.2 (9.2, 9.2)	N/A	10.0 (10.0, 10.0)
	2100	6.9 (7.0, 6.9)	6.9 (7.0, 6.9)	9.0 (9.0, 9.0)	9.0 (9.1, 9.0)	N/A	12.7 (12.8, 12.6)
Change in GDP per capita (% rel to 2010)	2050	170.3 (380.1, 130.9)	175.3 (386.2, 166.2)	104.3 (223.4, 98.7)	110.1 (233.8, 103.6)	N/A	55.1 (116.1, 46.7)
	2100	528.0 (1358.4, 408.2)	538.6 (1371.7, 504.7)	344.4 (827.4, 335.8)	356.6 (882.2, 323.3)	N/A	71.2 (159.7, 49.6)
Change in forest cover (Mkm^2)	2050	3.4 (9.4, -0.1)	0.6 (4.2, –0.7)	3.4 (7.0, –0.9)	–0.9 (2.9, –2.5)	N/A	–2.4 (–1.0, –4.0)
	2100	7.5 (15.8, 0.4)	3.9 (8.8, 0.2)	6.4 (9.5, –0.8)	–0.5 (5.9, –3.1)	N/A	–3.1 (–0.3, –5.5)
Change in cropland (Mkm^2)	2050	–1.2 (–0.3, –4.6)	0.1 (1.5, –3.2)	–1.2 (0.3, –2.0)	1.2 (2.7, –0.9)	N/A	2.3 (3.0, 1.2)
	2100	–5.2 (–1.8, –7.6)	–2.3 (–1.6, –6.4)	–2.9 (0.1, –4.0)	0.7 (3.1, –2.6)	N/A	3.4 (4.5, 1.9)
Change in energy cropland (Mkm^2)	2050	2.1 (5.0, 0.9)	0.8 (1.3, 0.5)	4.5 (7.0, 2.1)	1.5 (2.1, 0.1)	N/A	1.3 (2.0, 1.3)
	2100	4.3 (7.2, 1.5)	1.9 (3.7, 1.4)	6.6 (11.0, 3.6)	4.1 (6.3, 0.4)	N/A	4.6 (7.1, 1.5)
Change in pasture (Mkm^2)	2050	–4.1 (–2.5, –5.6)	–2.4 (–0.9, –3.3)	–4.8 (–0.4, –6.2)	–0.1 (1.6, –2.5)	N/A	2.1 (3.8, –0.1)
	2100	–6.5 (–4.8, –12.2)	–4.6 (–2.7, –7.3)	–7.6 (–1.3, –11.7)	–2.8 (1.9, –5.3)	N/A	2.0 (4.4, –2.5)
Change in other natural land (Mkm^2)	2050	0.5 (1.0, –4.9)	0.5 (1.7, –1.0)	–2.2 (0.6, –7.0)	–2.2 (0.7, –2.2)	N/A	–3.4 (–2.0, –4.4)
	2100	0.0 (7.1, –7.3)	1.8 (6.0, –1.7)	–2.3 (2.7, –9.6)	–3.4 (1.5, –4.7)	N/A	–6.2 (–5.4, –6.8)
Carbon price (2010 USD per tCO_2)[a]	2050	510.4 (4304.0, 150.9)	9.1 (35.2, 1.2)	756.4 (1079.9, 279.9)	37.5 (73.4, 13.6)	N/A	67.2 (75.1, 60.6)
	2100	2164.0 (350, 37.7, 262.7)	64.9 (286.7, 42.9)	4353.6 (10149.7, 2993.4)	172.3 (597.9, 112.1)	N/A	589.6 (727.2, 320.4)
Food price (Index 2010=1)	2050	1.2 (1.8, 0.8)	0.9 (1.1, 0.7)	1.6 (2.0, 1.4)	1.1 (1.2, 1.0)	N/A	1.2 (1.7, 1.1)
	2100	1.9 (7.0, 0.4)	0.8 (1.2, 0.4)	6.5 (13.1, 1.8)	1.1 (2.5, 0.9)	N/A	1.7 (3.4, 1.3)
Increase in Warming above pre-industrial (°C)	2050	1.5 (1.7, 1.5)	1.9 (2.1, 1.8)	1.6 (1.7, 1.5)	2.0 (2.0, 1.9)	N/A	2.0 (2.1, 2.0)
	2100	1.3 (1.3, 1.3)	2.6 (2.7, 2.4)	1.3 (1.3, 1.3)	2.6 (2.7, 2.4)	N/A	2.6 (2.6, 2.6)
Change in per capita demand for food, crops (% rel to 2010)[b]	2050	6.0 (10.0, 4.5)	9.1 (12.4, 4.5)	4.6 (6.7, –0.9)	7.9 (8.0, 5.2)	N/A	2.4 (5.0, 2.3)
	2100	10.1 (19.9, 4.8)	15.1 (23.9, 4.8)	11.6 (19.2, –10.8)	11.7 (19.2, 4.1)	N/A	2.0 (3.4, –1.0)
Change in per capita demand for food, animal products (% rel to 2010)[b,c]	2050	6.9 (45.0, –20.5)	17.9 (45.0, –20.1)	7.1 (36.0, 1.9)	10.3 (36.0, –4.2)	N/A	3.1 (5.9, 1.9)
	2100	–3.0 (19.8, –27.3)	21.4 (44.1, –26.9)	17.0 (39.6, –24.1)	20.8 (39.6, –5.3)	N/A	–7.4 (–0.7, –7.9)
Agriculture, forestry and other land-use (AFOLU) CH_4 Emissions (% relative to 2010)	2050	–39.0 (–3.8, –68.9)	–2.9 (22.4, –23.9)	–11.7 (31.4, –59.4)	7.5 (43.0, –15.5)	N/A	15.0 (20.1, 3.1)
	2100	–60.5 (–41.7, –77.4)	–47.6 (–24.4, –54.1)	–40.3 (33.1, –58.4)	–13.0 (63.7, –45.0)	N/A	8.0 (37.6, –9.1)
AFOLU N_2O Emissions (% relative to 2010)	2050	–13.1 (–4.1, –26.3)	0.1 (34.6, –14.5)	8.8 (38.4, –14.5)	25.4 (37.4, 5.5)	N/A	34.0 (50.8, 29.3)
	2100	–42.0 (4.3, –49.4)	–25.6 (–3.4, –51.2)	–1.7 (46.8, –37.8)	19.5 (66.7, –21.4)	N/A	53.9 (65.8, 30.8)
Cumulative Energy CO_2 Emissions until 2100 ($GtCO_2$)		428.2 (1009.9, 307.6)	2787.6 (3213.3, 2594.0)	380.8 (552.8, –9.4)	2642.3 (2928.3, 2515.8)	N/A	2294.5 (2447.4, 2084.6)
Cumulative AFOLU CO_2 Emissions until 2100 ($GtCO_2$)		–127.3 (5.9, –683.0)	–54.9 (52.1, –545.2)	–126.8 (153.0, –400.7)	40.8 (277.0, –372.9)	N/A	188.8 (426.6, 77.9)

[a] SSP2–19 is infeasible in two models. One of these models sets the maximum carbon price in SSP1–19; the carbon price range is smaller for SSP2–19 as this model is excluded there. Carbon prices are higher in SSP2–19 than SSP1–19 for every model that provided both simulations.
[b] Food demand estimates include waste.
[c] Animal product demand includes meat and dairy.

Cross-Chapter Box 9 (continued)

Climate change results in higher impacts and risks in the 4.5 W m^{-2} world than in the 1.9 W m^{-2} world for a given SSP and these risks are exacerbated in SSP3 compared to SSP1 and SSP2 due to the population's higher exposure and vulnerability. For example, the risk of fire is higher in warmer worlds; in the 4.5 W m^{-2} world, the population living in fire prone regions is higher in SSP3 (646 million) than in SSP2 (560 million) (Knorr et al. 2016). Global exposure to multi-sector risk quadruples between 1.5°C[1] and 3°C and is a factor of six higher in SSP3-3°C than in SSP1-1.5°C (Byers et al. 2018). Future risks resulting from desertification, land degradation and food insecurity are lower in SSP1 compared to SSP3 at the same level of warming. For example, the transition moderate-to-high risk of food insecurity occurs between 1.3 and 1.7°C for SSP3, but not until 2.5 to 3.5°C in SSP1 (Section 7.2).

Summary

Future pathways for climate and land use include portfolios of response and policy options. Depending on the response options included, policy portfolios implemented, and other underlying socio-economic drivers, these pathways result in different land-use consequences and their contribution to climate change mitigation. Agricultural area declines by more than 5 Mkm^2 in one SSP but increases by as much as 5 Mkm^2 in another. The amount of energy cropland ranges from nearly zero to 11 Mkm^2, depending on the SSP and the warming target. Forest area declines in SSP3 but increases substantially in SSP1. Subsequently, these pathways have different implications for risks related to desertification, land degradation, food insecurity, and terrestrial GHG fluxes, as well as ecosystem services, biodiversity, and other aspects of sustainable development.

7.5.6.1 Trade-offs and synergies between ecosystem services (ES)

Unplanned or unintentional trade-offs and synergies between policy driven response options related to ecosystem services (ES) can happen over space (e.g., upstream-downstream, integrated watershed management, Section 3.7.5.2) or intensify over time (reduced water in future dry-season due to growing tree plantations, Section 6.4.1). Trade-offs can occur between two or more ES (land for climate mitigation vs food; Sections 6.2, 6.3, 6.4, Cross-Chapter Box 8 in Chapter 6; Cross-Chapter Box 9 in Chapters 6 and 7), and between scales, such as forest biomass-based livelihoods versus global ES carbon storage (Chhatre and Agrawal 2009) (*medium evidence*, *medium agreement*). Trade-offs can be reversible or irreversible (Rodríguez et al. 2006; Elmqvist et al. 2013) (for example, a soil carbon sink is reversible) (Section 6.4.1.1).

Although there is *robust evidence* and *high agreement* that ES are important for human well-being, the relationship between poverty alleviation and ES can be surprisingly complex, understudied and dependent on the political economic context; current evidence is largely about provisioning services and often ignores multiple dimensions of poverty (Suich et al. 2015; Vira et al. 2012). Spatially explicit mapping and quantification of stakeholder choices in relation to distribution of various ES can help enhance synergies and reduce trade-offs (Turkelboom et al. 2018; Locatelli et al. 2014) (Section 7.5.5).

7.5.6.2 Sustainable Development Goals (SDGs): Synergies and trade-offs

The Sustainable Development Goals (SDGs) are an international persuasive policy instrument that apply to all countries, and measure sustainable and socially just development of human societies at all scales of governance (Griggs et al. 2013). The UN SDGs rest on the premise that the goals are mutually reinforcing and there are inherent linkages, synergies and trade-offs (to a greater or lesser extent) between and within the sub-goals (Fuso Nerini et al. 2018; Nilsson et al. 2016b; Le Blanc 2015). There is *high confidence* that opportunities, trade-offs and co-benefits are context – and region-specific and depend on a variety of political, national and socio-economic factors (Nilsson et al. 2016b) depending on perceived importance by decision-makers and policymakers (Figure 7.7 and Table 7.6). Aggregation of targets and indicators at the national level can mask severe biophysical and socio-economic trade-offs at local and regional scales (Wada et al. 2016).

There is *medium evidence* and *high agreement* that SDGs must not be pursued independently, but in a manner that recognises trade-offs and synergies with each other, consistent with a goal of 'policy coherence'. Policy coherence also refers to spatial trade-offs and geopolitical implications within and between regions and countries implementing SDGs. For instance, supply-side food security initiatives of land-based agriculture are impacting on marine fisheries globally through creation of dead-zones due to agricultural run-off (Diaz and Rosenberg 2008).

SDGs 6 (clean water and sanitation), 7 (affordable and clean energy) and 9 (industry, innovation and infrastructure) are important SDGs related to mitigation with adaptation co-benefits, but they have local

1 Pathways that limit radiative forcing in 2100 to 1.9 W m^{-2} result in median warming in 2100 to 1.5°C in 2100 (Rogelj et al. 2018b). Pathways limiting radiative forcing in 2100 to 4.5 W m^{-2} result in median warming in 2100 above 2.5°C (IPCC 2014).

trade-offs with biodiversity and competing uses of land and rivers (see Case study: Green energy: Biodiversity conservation vs global environment targets) (*medium evidence*, *high agreement*) (Bogardi et al. 2012; Nilsson and Berggren 2000; Hoeinghaus et al. 2009; Winemiller et al. 2016). This has occurred despite emerging knowledge about the role that rivers and riverine ecosystems play in human development and in generating global, regional and local ES (Nilsson and Berggren 2000; Hoeinghaus et al. 2009). The transformation of river ecosystems for irrigation, hydropower and water requirements of societies worldwide is the biggest threat to freshwater and estuarine biodiversity and ecosystems services (Nilsson and Berggren 2000; Vörösmarty et al. 2010). These projects address important energy and water-related demands, but their economic benefits are often overestimated in relation to trade-offs with respect to food (river capture fisheries), biodiversity and downstream ES (Winemiller et al. 2016). Some trade-offs and synergies related to SDG7 impact on aspirations of greater welfare and well-being, as well as physical and social infrastructure for sustainable development (Fuso Nerini et al. 2018) (Section 7.5.6.1, where trade-offs exist between climate mitigation and food).

There are also spatial trade-offs related to large river diversion projects and export of 'virtual water' through water-intensive crops produced in one region and exported to another, with implications for food security, water security and downstream ES of the exporting region (Hanasaki et al. 2010; Verma et al. 2009). Synergies include cropping adaptations that increase food system production and eliminate hunger (SDG2) (Rockström et al. 2017; Lipper et al. 2014a; Neufeldt et al. 2013). Well-adapted agricultural systems are shown to have synergies, positive returns on investment and contribute to safe drinking water, health, biodiversity and equity goals (DeClerck 2016). Assessing the water footprint of different sectors at the river basin scale can provide insights for interventions and decision-making (Zeng et al. 2012).

Sometimes the trade-offs in SDGs can arise in the articulation and nested hierarchy of 17 goals and the targets under them. In terms of aquatic life and ecosystems, there is an explicit SDG for sustainable management of marine life (SDG 14, Life below water). There is no equivalent goal exclusively for freshwater ecosystems, but hidden under SDG 6 (Clean water and sanitation) out of six listed targets, the sixth target is about protecting and restoring water-related ecosystems, which suggests a lower order of global priority compared to being listed as a goal in itself (e.g., SDG 14).

There is *limited evidence* and *limited agreement* that binary evaluations of individual SDGs and synergies and trade-offs that categorise interactions as either 'beneficial' or 'adverse' may be subjective and challenged further by the fact that feedbacks can often not be assigned as unambiguously positive or negative (Blanc et al. 2017). The IPCC Special Report on Global Warming of 1.5°C (SR15) notes: 'A reductive focus on specific SDGs in isolation may undermine the long-term achievement of sustainable climate change mitigation' (Holden et al. 2017). Greater work is needed to tease out these relationships; studies have started that include quantitative modelling (see Karnib 2017) and nuanced scoring scales (ICSU 2017) of these relationships.

A nexus approach is increasingly being adopted to explore synergies and trade-offs between a select subset of goals and targets (such as the interaction between water, energy and food – see for example, Yumkella and Yillia 2015; Conway et al. 2015; Ringler et al. 2015). However, even this approach ignores systemic properties and interactions across the system as a whole (Weitz et al. 2017a). Pursuit of certain targets in one area can generate rippling effects across the system, and these in turn can have secondary impacts on yet other targets. Weitz et al. (2017a) found that SDG target 13.2 (climate change policy/planning) is influenced by actions in six other targets. SDG 13.1 (climate change adaption) and also SDG 2.4 (food production) receive the most positive influence from progression in other targets.

There is *medium evidence* and *high agreement* that, to be effective, truly sustainable, and to reduce or mitigate emerging risks, SDGs need knowledge dissemination and policy initiatives that recognise and assimilate concepts of co-production of ES in socio-ecological systems, cross-scale linkages, uncertainty, spatial and temporal trade-offs between SDGs and ES that acknowledge biophysical, social and political constraints and understand how social change occurs at various scales (Rodríguez et al. 2006; Norström et al. 2014; Palomo et al. 2016). Several methods and tools are proposed in literature to address and understand SDG interactions. Nilsson et al. (2016a) suggest going beyond a simplistic framing of synergies and trade-offs to understanding the various relationship dimensions, and proposing a seven-point scale to understand these interactions.

This approach, and the identification of clusters of synergy, can help indicate that government ministries work together or establish collaborations to reach their specific goals. Finally, context-specific analysis is needed. Synergies and trade-offs will depend on the natural resource base (such as land or water availability), governance arrangements, available technologies, and political ideas in a given location (Nilsson et al. 2016b). Figure 7.7 shows that, at the global scale, there is less uncertainty in the evidence surrounding SDGs, but also less agreement on norms, priorities and values for SDG implementation. Although there is *some agreement* on the regional and local scale surrounding SDGs, there is *higher certainty* on the science surrounding ES.

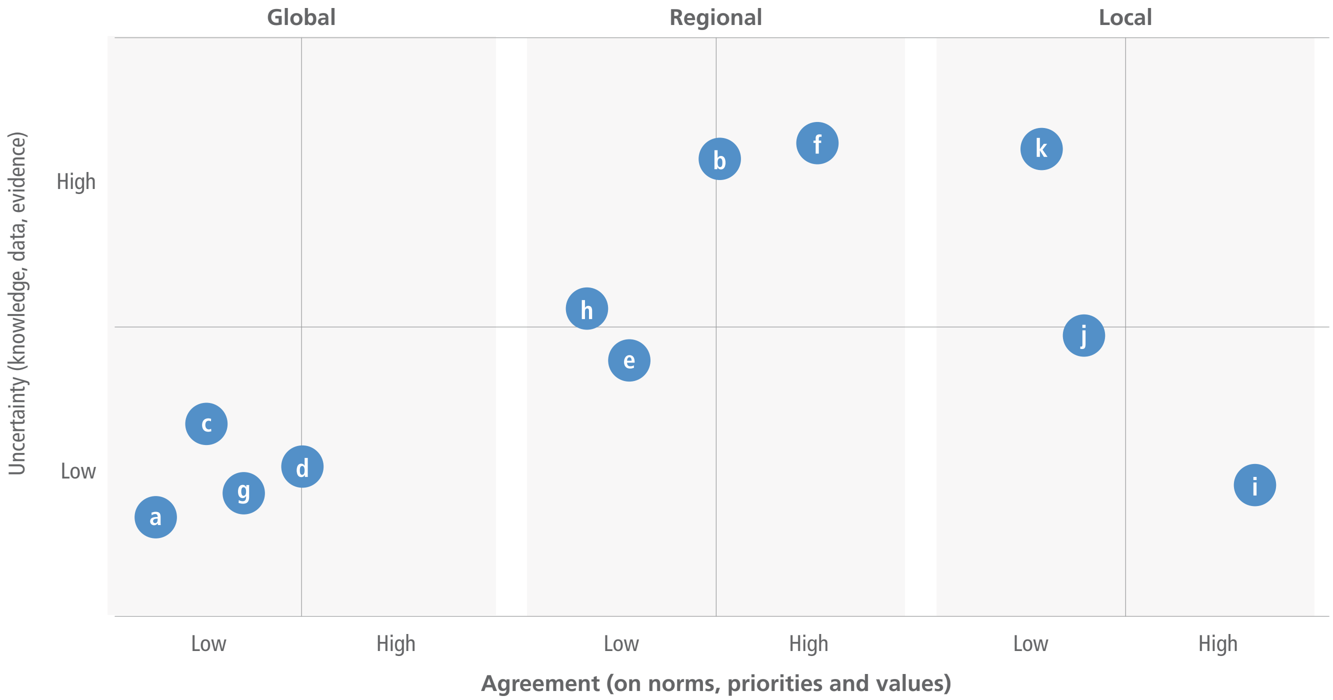


Figure 7.7 and Table 7.6 | Risks at various scales, levels of uncertainty and agreement in relation to trade-offs among SDGs and other goals.

	Land-climate-society hazard	SDGs impacted by or involved in mutual trade-offs	Selected literature
a	Decline of freshwater and riverine ecosystems	2, 3, 6, 7, 8, 12, 16, 18	Falkenmark 2001; Zarfl et al. 2014; Canonico et al. 2005
b	Forest browning	3, 8, 13, 15	Verbyla 2011; Krishnaswamy et al. 2014; McDowell and Allen 2015b; Anderegg et al. 2013; Samanta et al. 2010
c	Exhaustion of groundwater	1, 3, 6, 8, 11, 12, 13, 18	Barnett and O'Neill 2010; Wada et al. 2010; Harootunian 2018; Dalin et al. 2017; Rockström, Johan Steffen et al. 2009; Falkenmark 2001
d	Loss of biodiversity	6, 7, 12, 15, 18	Pereira et al. 2010; Pascual et al. 2017; Pecl et al. 2017; Jumani et al. 2017, 2018
e	Extreme events in cities and towns	3, 6, 11, 13	Douglas et al. 2008; Stone et al. 2010; Chang et al. 2007; Hanson et al. 2011
f	Stranded assets	8, 9, 11, 12, 13	Ansar et al. 2013; Chasek et al. 2015; Melvin et al. 2017; Surminski 2013; Hallegatte et al. 2013; Larsen et al. 2008; Nicholls and Cazenave 2010
g	Expansion of the agricultural frontier into tropical forests	15, 13	Celentano et al. 2017; Nepstad et al. 2008; Bogaerts et al. 2017; Fearnside 2015; Beuchle et al. 2015; Grecchi et al. 2014
h	Food and nutrition security	2, 1, 3, 10, 11	Hasegawa et al. 2018a; Frank et al. 2017; Fujimori et al. 2018b; Zhao et al. 2017
i	Emergence of infectious diseases	3, 1, 6, 10, 11, 12, 13	Wu et al. 2016; Patz et al. 2004; McMichael et al. 2006; Young et al. 2017b; Smith et al. 2014a; Tjaden et al. 2017; Naicker 2011
j	Decrease in agricultural productivity	2, 1, 3, 10, 11, 13	Porter et al. 2014; Müller et al. 2013; Rosenzweig et al. 2014
k	Expansion of farm and fish ponds	1, 2, 3, 6, 8, 10, 13, 14	Kale 2017; Boonstra and Hanh 2015

Sustainable Development Goals

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure
10. Reduced inequality
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on Land
16. Peace and justice strong institutions
17. Partnerships to achieve the goals

7.5.6.3 Forests and agriculture

Retaining existing forests, restoring degraded forest and afforestation are response options for climate change mitigation with adaptation benefits (Section 6.4.1). Policies at various levels of governance that foster ownership, autonomy, and provide incentives for forest cover can reduce trade-offs between carbon sinks in forests and local livelihoods (especially when the size of forest commons is sufficiently large) (Chhatre and Agrawal 2009; Locatelli et al. 2014) (see Table 7.6 this section; Case study: Forest conservation instruments: REDD+ in the Amazon and India, Section 7.4.6).

Forest restoration for mitigation through carbon sequestration and other ES or co-benefits (e.g., hydrologic, non-timber forest products, timber and tourism) can be passive or active (although both types largely exclude livestock). Passive restoration is more economically viable in relation to restoration costs as well as co-benefits in other ES, calculated on a net present value basis, especially under flexible carbon credits (Cantarello et al. 2010). Restoration can be more cost effective with positive socio-economic and biodiversity conservation outcomes, if costly and simplistic planting schemes are avoided (Menz et al. 2013). Passive restoration takes longer to demonstrate co-benefits and net economic gains. It can be confused with land abandonment in some regions and countries, and therefore secure land-tenure at individual or community scales is important for its success (Zahawi et al. 2014). Potential approaches include improved markets and payment schemes for ES (Tengberg et al. 2016) (Section 7.4.6).

Proper targeting of incentive schemes and reducing poverty through access to ES requires knowledge regarding the distribution of beneficiaries, information about those whose livelihoods are likely to be impacted, and in what manner (Nayak et al. 2014; Loaiza et al. 2015; Vira et al. 2012). Institutional arrangements to govern ecosystems are believed to synergistically influence maintenance of carbon storage and forest-based livelihoods, especially when they incorporate local knowledge and decentralised decision-making (Chhatre and Agrawal 2009). Earning carbon credits from reforestation with native trees involves the higher cost of certification and validation processes, increasing the temptation to choose fast-growing (perhaps non-native) species with consequences for native biodiversity. Strategies and policies that aggregate landowners or forest dwellers are needed to reduce the cost to individuals and payment for ecosystem services (PES) schemes can generate synergies (Bommarco et al. 2013; Chhatre and Agrawal 2009). Bundling several PES schemes that address more than one ES can increase income generated by forest restoration (Brancalion et al. 2012).

In the forestry sector, there is evidence that adaptation and mitigation can be fostered in concert. A recent assessment of the California Forestry Offset Project shows that, by compensating individuals and industries for forest conservation, such programmes can deliver mitigation and sustainability co-benefits (Anderson et al. 2017). Adaptive forest management focusing on reintroducing native tree species can provide both mitigation and adaptation benefit by reducing fire risk and increasing carbon storage (Astrup et al. 2018).

In the agricultural sector, there has been little published empirical work on interactions between adaptation and mitigation policies. Smith and Oleson (2010) describe potential relationships, focusing particularly on the arable sector, predominantly on mitigation efforts, and more on measures than policies. The considerable potential of the agro-forestry sector for synergies and contributing to increasing resilience of tropical farming systems is discussed in Verchot et al. (2007) with examples from Africa.

Climate-smart agriculture (CSA) has emerged in recent years as an approach to integrate food security and climate challenges. The three pillars of CSA are to: (1) adapt and build resilience to climate change; (2) reduce GHG emissions, and; (3) sustainably increase agricultural productivity, ultimately delivering 'triple-wins' (Lipper et al. 2014c). While the idea is conceptually appealing, a range of criticisms, contradictions and challenges exist in using CSA as the route to resilience in global agriculture, notably around the political economy (Newell and Taylor 2017), the vagueness of the definition, and consequent assimilation by the mainstream agricultural sector, as well as issues around monitoring, reporting and evaluation (Arakelyan et al. 2017).

Land-based mitigation is facing important trade-offs with food production, biodiversity and local biogeophysical effects (Humpenöder et al. 2017; Krause et al. 2017; Robledo-Abad et al. 2017; Boysen et al. 2016, 2017a,b). Synergies between bioenergy and food security could be achieved by investing in a combination of instruments, including technology and innovations, infrastructure, pricing, flex crops, and improved communication and stakeholder engagement (Kline et al. 2017). Managing these trade-offs might also require demand-side interventions, including dietary change incentives (Section 5.7.1).

Synergies and trade-offs also result from interaction between policies (Urwin and Jordan 2008) at different levels of policy (vertical) and across different policies (horizontal) – see also Section 7.4.8. If policy mixes are designed appropriately, acknowledging and incorporating trade-offs and synergies, they are more apt to deliver an outcome such as transitioning to sustainability (Howlett and Rayner 2013; Huttunen et al. 2014) (*medium evidence* and *medium agreement*). However, there is *medium evidence* and *medium agreement* that evaluating policies for coherence in responding to climate change and its impacts is not occurring, and policies are instead reviewed in a fragmented manner (Hurlbert and Gupta 2016).

7.5.6.4 Water, food and aquatic ecosystem services (ES)

Trade-offs between some types of water use (e.g., irrigation for food security) and other ecosystem services (ES) are expected to intensify under climate change (Hanjra and Ejaz Qureshi 2010). There is an urgency to develop approaches to understand and communicate this to policymakers and decision-makers (Zheng et al. 2016). Reducing water use in agriculture (Mekonnen and Hoekstra 2016) through policies on both the supply and demand side, such as a shift to less water-intensive crops (Richter et al. 2017; Fishman et al. 2015), and a shift in diets (Springmann et al. 2016) has the potential to reduce trade-offs between food security and freshwater aquatic ES (*medium* *evidence*, *high agreement*). There is strong evidence that improved efficiency in irrigation can actually increase overall water use in agriculture, and therefore its contribution to improved flows in rivers is questionable (Ward and Pulido-Velazquez 2008).

There are now powerful new analytical approaches, high-resolution data and decision-making tools that help to predict cumulative impacts of dams, assess trade-offs between engineering and environmental goals, and can help funders and decision-makers compare alternative sites or designs for dam-building as well as to manage flows in regulated rivers based on experimental releases and adaptive learning. This could minimise ecological costs and maximise synergies with other development goals under climate change (Poff et al. 2003; Winemiller et al. 2016). Furthermore, the adoption of metrics based on the emerging concept of Nature's Contributions to People (NCP) under the IPBES framework brings in non-economic instruments and values that, in combination with conventional valuation of ES approaches, could elicit greater support for non-consumptive water use of rivers for achieving SDG goals (De Groot et al. 2010; Pascual et al. 2017).

7.5.6.5 Considering synergies and trade-offs to avoid maladaptation

Coherent policies that consider synergies and trade-offs can also reduce the likelihood of maladaptation, which is the opposite of sustainable adaptation (Magnan et al. 2016). Sustainable adaptation 'contributes to socially and environmentally sustainable development pathways including both social justice and environmental integrity' (Eriksen et al. 2011). In IPCC's Fifth Assessment Report (AR5) there was *medium evidence* and *high agreement* that maladaptation is 'a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of a group to future climate change' (Noble et al. 2014). AR5 recognised that maladaptation arises not only from inadvertent, badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from planned actions (Noble et al. 2014).

Some maladaptations are only beginning to be recognised as we become aware of unintended consequences of decisions. An example prevalent across many countries is irrigation as an adaptation to water scarcity. During a drought from 2007–2009 in California, farmers adapted by using more groundwater, thereby depleting groundwater elevation by 15 metres. This volume of groundwater depletion is unsustainable environmentally and also emits GHG emissions during the pumping (Christian-Smith et al. 2015). Despite the three years of drought, the agricultural sector performed financially well, due to the groundwater use and crop insurance payments. Drought compensation programmes through crop insurance policies may reduce the incentive to shift to lower water-use crops, thereby perpetuating the maladaptive situation. Another example of maladaptation that may appear as adaptation to drought is pumping out groundwater and storing in surface farm ponds, with consequences for water justice, inequity and sustainability (Kale 2017). These examples highlight the potential for maladaptation from farmers' adaptation decisions as well as the unintended consequences of policy choices; the examples illustrate the findings of Barnett and O'Neill (2010) that maladaptation can include: high opportunity costs (including economic, environmental, and social); reduced incentives to adapt (adaptation measures that reduce incentives to adapt by not addressing underlying causes); and path dependency or trajectories that are difficult to change.

In practice, maladaptation is a specific instance of policy incoherence, and it may be useful to develop a framework in designing policy to avoid this type of trade-off. This would specify the type, aim and target audience of an adaptation action, decision, project, plan, or policy designed initially for adaptation, but actually at high risk of inducing adverse effects, either on the system in which it was developed, or another connected system, or both. The assessment requires identifying system boundaries, including temporal and geographical scales at which the outcomes are assessed (Magnan 2014; Juhola et al. 2016). National-level institutions that cover the spectrum of sectors affected, or enhanced collaboration between relevant institutions, is expected to increase the effectiveness of policy instruments, as are joint programmes and funds (Morita and Matsumoto 2018).

As new knowledge about trade-offs and synergies amongst land-climate processes emerges regionally and globally, concerns over emerging risks and the need for planning policy responses grow. There is *medium evidence* and *medium agreement* that trade-offs currently do not figure into existing climate policies including NDCs and SDGs being vigorously pursued by some countries (Woolf et al. 2018). For instance, the biogeophysical co-benefits of reduced deforestation and re/afforestation measures (Chapter 6) are usually not accounted for in current climate policies or in the NDCs, but there is increasing scientific evidence to include them as part of the policy design (Findell et al. 2017; Hirsch et al. 2018; Bright et al. 2017).

Case study | Green energy: Biodiversity conservation vs global environment targets?

Green and renewable energy and transportation are emerging as important parts of climate change mitigation globally (*medium evidence, high agreement*) (McKinnon 2010; Zarfl et al. 2015; Creutzig et al. 2017). Evidence is, however, emerging across many biomes (from coastal to semi-arid and humid) about how green energy may have significant trade-offs with biodiversity and ecosystem services, thus demonstrating the need for closer environmental scrutiny and safeguards (Gibson et al. 2017; Hernandez et al. 2015). In most cases, the accumulated impact of pressures from decades of land use and habitat loss set the context within which the potential impacts of renewable energy generation need to be considered.

Until recently, small hydropower projects (SHPs) were considered environmentally benign compared to large dams. SHPs are poorly understood, especially since the impacts of clusters of small dams are just becoming evident (Mantel et al. 2010; Fencl et al. 2015; Kibler and Tullos 2013). SHPs (<25/30 MW) are labelled 'green' and are often exempt from environmental scrutiny (Abbasi and Abbasi 2011; Pinho et al. 2007; Premalatha et al. 2014b; Era Consultancy 2006). Being promoted in mountainous global biodiversity hotspots, SHPs have changed the hydrology, water quality and ecology of headwater streams and neighbouring forests significantly. SHPs have created dewatered stretches of stream immediately downstream and introduced sub-daily to sub-weekly hydro-pulses that have transformed the natural dry-season flow regime. Hydrologic and ecological connectivity have been impacted, especially for endemic fish communities and forests in some sites of significant biodiversity values (*medium evidence, medium agreement*) (Jumani et al. 2017, 2018; Chhatre and Lakhanpal 2018; Anderson et al. 2006; Grumbine and Pandit 2013). In some sites, local communities have opposed SHPs due to concerns about their impact on local culture and livelihoods (Jumani et al. 2017, 2018; Chhatre and Lakhanpal 2018).

Semi-arid and arid regions are often found suitable for wind and solar farms which may impact endemic biodiversity and endangered species (Collar et al. 2015, Thaker, M, Zambre, A. Bhosale 2018). The loss of habitat for these species over the decades has been largely due to agricultural intensification driven by irrigation and bad management in designated reserves (Collar et al. 2015; Ledec, George C.; Rapp, Kennan W.; Aiello 2011) but intrusion of power lines is a major worry for highly endangered species such as the Great Indian Bustard (Great Indian Bustard (Ardeotis nigriceps) and conservation and mitigation efforts are being planned to address such concerns (Government of India 2012). In many regions around the world, wind-turbines and solar farms pose a threat to many other species especially predatory birds and insectivorous bats (*medium evidence, medium agreement*) (Thaker, M, Zambre, A. Bhosale 2018) and disrupt habitat connectivity (Northrup and Wittemyer 2013).

Additionally, conversion of rivers into waterways has emerged as a fuel-efficient (low carbon emitting) and environment-friendly alternative to surface land transport (IWAI 2016; Dharmadhikary, S., and Sandbhor 2017). India's National Waterways seeks to cut transportation time and costs and reduce carbon emissions from road transport (Admin 2017). There is some evidence that dredging and under-water noise could impact the water quality, human health and habitat of fish species (Junior et al. 2012; Martins et al. 2012), disrupt artisanal fisheries and potentially impact species that rely on echo-location (*low evidence, medium agreement*) (Dey Mayukh 2018). Off-shore renewable energy projects in coastal zones have been known to have similar impacts on marine fauna (Gill 2005). The Government of India has decided to support studies of the impact of waterways on the endangered Gangetic dolphin in order in order to plan mitigation measures.

Responses to mitigating and reducing the negative impacts of small dams include changes in SHP operations and policies to enable the conservation of river fish diversity. These include mandatory environmental impact assessments, conserving remaining undammed headwater streams in regulated basins, maintaining adequate environmental flows, and implementing other adaptation measures based on experiments with active management of fish communities in impacted zones (Jumani et al. 2018). Location of large solar farms needs to be carefully scrutinised (Sindhu et al. 2017). For mitigating negative impacts of power lines associated with solar and wind farms in bustard habitats, suggested measures include diversion structures to prevent collision, underground cables and avoidance in core wildlife habitat, as well as incentives for maintaining low-intensity rainfed agriculture and pasture around existing reserves, and curtailing harmful infrastructure in priority areas (Collar et al. 2015). Mitigation for minimising the ecological impact of inland waterways on biodiversity and fisheries is more complicated, but may involve improved boat technology to reduce underwater noise, maintaining ecological flows and thus reduced dredging, and avoidance in key habitats (Dey Mayukh 2018).

The management of ecological trade-offs of green energy and green infrastructure and transportation projects may be crucial for long-term sustainability and acceptance of emerging low-carbon economies.

7.6 Governance: Governing the land–climate interface

Building on the definition in Section 7.1.2, governance situates decision-making and selection or calibration of policy instruments within the reality of the multitude of actors operating in respect of land and climate interactions. Governance includes all of the processes, structures, rules and traditions that govern; governance processes may be undertaken by actors including a government, market, organisation, or family (Bevir 2011). Governance processes determine how people in societies make decisions (Patterson et al. 2017) and involve the interactions among formal and informal institutions (Section 7.4.1) through which people articulate their interests, exercise their legal rights, meet their legal obligations, and mediate their differences (Plummer and Baird 2013).

The act of governance 'is a social function centred on steering collective behaviour toward desired outcomes [sustainable climate-resilient development] and away from undesirable outcomes' (Young 2017a). This definition of governance allows for it to be decoupled from the more familiar concept of government and studied in the context of complex human–environment relations and environmental and resource regimes (Young 2017a) and used to address the interconnected challenges facing food and agriculture (FAO 2017b). These challenges include assessing, combining, and implementing policy instruments at different governance levels in a mutually reinforcing way, managing trade-offs while capitalising on synergies (Section 7.5.6), and employing experimentalist approaches for improved and effective governance (FAO 2017b), for example, adaptive climate governance (Section 7.6.3). Emphasising governance also represents a shift of traditional resource management (focused on hierarchical state control) towards recognition that political and decision-making authority can be exercised through interlinked groups of diverse actors (Kuzdas et al. 2015).

This section will start by describing institutions and institutional arrangements – the core of a governance system (Young 2017) – that build adaptive and mitigative capacity. The section then outlines modes, levels and scales of governance for sustainable climate-resilient development. It does on to describe adaptive climate governance that responds to uncertainty, and explore institutional dimensions of adaptive governance that create an enabling environment for strong institutional capital. We then discuss land tenure (an important institutional context for effective and appropriate selection of policy instruments), and end with the participation of people in decision-making through inclusive governance.

7.6.1 Institutions building adaptive and mitigative capacity

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction. Institutions can be formal – such as laws, policies, and structured decision-making processes (Section 7.5.1.1) – or informal – such as norms, conventions, and decision-making following customary norms and habits (Section 7.5.1.2). Organisations – such as parliaments, regulatory agencies, private firms, and community bodies – as well as people, develop and act in response to institutional frameworks and the incentives they frame. 'Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization' (IPCC 2014d, p. 1768). Nations with 'well developed institutional systems are considered to have greater adaptive capacity', and better institutional capacity to help deal with risks associated with future climate change (IPCC, 2001, p. 896). Institutions may also prevent the development of adaptive capacity when they are 'sticky' or characterised by strong path dependence (Mahoney 2000; North 1991) and prevent changes that are important to address climate change (Section 7.4.9).

Formal and informal governance structures are composed of these institutionalised rule systems that determine vulnerability as they influence power relations, risk perceptions and establish the context wherein risk reduction, adaptation and vulnerability are managed (Cardona 2012). Governance institutions determine the management of a community's assets, the community members' relationships with one another, and with natural resources (Hurlbert and Diaz 2013). Traditional or locally evolved institutions, backed by cultural norms, can contribute to resilience and adaptive capacity. Anderson et al. (2010) suggest that these are a particular feature of dry land societies that are highly prone to environmental risk and uncertainty. Concepts of resilience, and specifically the resilience of socio-ecological systems, have advanced analysis of adaptive institutions and adaptive governance in relation to climate change and land (Boyd and Folke 2011a). In their characterisation, 'resilience is the ability to reorganise following crisis, continuing to learn, evolving with the same identity and function, and also innovating and sowing the seeds for transformation. It is a central concept of adaptive governance' (Boyd and Folke 2012). In the context of complex and multi-scale socio-ecological systems, important features of adaptive institutions that contribute to resilience include the characteristics of an adaptive governance system (Section 7.6.6).

There is *high confidence* that adaptive institutions have a strong learning dimension and include:

1. Institutions advancing the capacity to learn through availability, access to, accumulation of, and interpretation of information (such as drought projections, costing of alternatives land, food, and water strategies). Government-supported networks, learning platforms, and facilitated interchange between actors with boundary and bridging organisations, creating the necessary self-organisation to prepare for the unknown. Through transparent, flexible networks, whole sets of complex problems of land, food and climate can be tackled to develop shared visions and critique land and food management systems assessing gaps and generating solutions.
2. Institutions advancing learning by experimentation (in interpretation of information, new ways of governing, and treating policy as an ongoing experiment) through many interrelated decisions, but especially those that connect the social to the ecological and entail anticipatory planning by considering a longer-term time frame. Mechanisms to do so include ecological stewardship, and rituals and beliefs of indigenous societies that sustain ES.

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3. Institutions that decide on pathways to realise system change through cultural, inter and intra organisational collaboration, with a flexible regulatory framework allowing for new cognitive frames of 'sustainable' land management and 'safe' water supply that open alternative pathways (Karpouzoglou et al. 2016; Bettini et al. 2015; Boyd et al. 2015; Boyd and Folke 2011b, and 2012).

Shortcomings of resilience theory include limits in relation to its conceptualisation of social change (Cote and Nightingale 2012), its potential to be used as a normative concept, implying politically prescriptive policy solutions (Thorén and Olsson 2017; Weichselgartner and Kelman 2015; Milkoreit et al. 2015), its applicability to local needs and experiences (Forsyth 2018), and its potential to hinder evaluation of policy effectiveness (Newton 2016; Olsson et al. 2015b). Regardless, concepts of adaptive institutions building adaptive capacity in complex socio-ecological systems governance have progressed (Karpouzoglou et al. 2016; Dwyer and Hodge 2016) in relation to adaptive governance (Koontz et al. 2015).

The study of institutions of governance, levels, modes, and scale of governance, in a multi-level and polycentric fashion is important because of the multi-scale nature of the challenges to resilience, dissemination of ideas, networking and learning.

7.6.2 Integration – Levels, modes and scale of governance for sustainable development

Different types of governance can be distinguished according to intended levels (e.g., local, regional, global), domains (national, international, transnational), modes (market, network, hierarchy), and scales (global regimes to local community groups) (Jordan et al. 2015b). Implementation of climate change adaptation and mitigation has been impeded by institutional barriers, including multi-level governance and policy integration issues (Biesbroek et al. 2010). To overcome these barriers, climate governance has evolved significantly beyond the national and multilateral domains that tended to dominate climate efforts and initiatives during the early years of the UNFCCC. The climate challenge has been placed in an Earth System context, showing the existence of complex interactions and governance requirements across different levels, and calling for a radical transformation in governance, rather than minor adjustments (Biermann et al. 2012). Climate governance literature has expanded since AR5 in relation to the sub-national and transnational levels, but all levels and their interconnection is important. Expert thinking has evolved from implementing good governance at high levels (with governments) to a decentred problem-solving approach consistent with adaptive governance. This approach involves iterative bottom-up and experimental mechanisms that might entail addressing tenure of land or forest management through a territorial approach to development, thereby supporting multi-sectoral governance in local, municipal and regional contexts (FAO 2017b).

Local action in relation to mitigation and adaptation continues to be important by complementing and advancing global climate policy (Ostrom 2012). Sub-national governance efforts for climate policy, especially at the level of cities and communities, have become significant during the past decades (*medium evidence*, *medium agreement*) (Castán Broto 2017; Floater et al. 2014; Albers et al. 2015; Archer et al. 2014). A transformation of sorts has been underway through deepening engagement from the private sector and NGOs as well as government involvement at multiple levels. It is now recognised that business organisations, civil society groups, citizens, and formal governance all have important roles in governance for sustainable development (Kemp et al. 2005).

Transnational governance efforts have increased in number, with applications across different economic sectors, geographical regions, civil society groups and NGOs. When it comes to climate mitigation, transnational mechanisms generally focus on networking and may not necessarily be effective in terms of promoting real emissions reductions (Michaelowa and Michaelowa 2017). However, acceleration in national mitigation measures has been determined to coincide with landmark international events such as the lead up to the Copenhagen Climate Change Conference 2009 (Iacobuta et al. 2018). There is a tendency for transnational governance mechanisms to lack monitoring and evaluation procedures (Jordan et al. 2015a).

To address shortcomings of transnational governance, polycentric governance considers the interaction between actors at different levels of governance (local, regional, national, and global) for a more nuanced understanding of the variation in diverse governance outcomes in the management of common-pool resources (such as forests) based on the needs and interests of citizens (Nagendra and Ostrom 2012). A more 'polycentric climate governance' system has emerged that incorporates bottom-up initiatives that can support and synergise with national efforts and international regimes (Ostrom 2010). Although it is clear that many more actors and networks are involved, the effectiveness of a more polycentric system remains unclear (Jordan et al. 2015a).

There is *high confidence* that a hybrid form of governance, combining the advantages of centralised governance (with coordination, stability, compliance) with those of more horizontal structures (that allow flexibility, autonomy for local decision-making, multi-stakeholder engagement, co-management) is required for effective mainstreaming of mitigation and adaptation in sustainable land and forest management (Keenan 2015; Gupta 2014; Williamson and Nelson 2017; Liniger et al. 2019). Polycentric institutions self-organise, developing collective solutions to local problems as they arise (Koontz et al. 2015). The public sector (governments and administrative systems) are still important in climate change initiatives as these actors retain the political will to implement and make initiatives work (Biesbroek et al. 2018).

Sustainable development hinges on the holistic integration of interconnected land and climate issues, sectors, levels of government, and policy instruments (Section 7.4.8) that address the increasing volatility in oscillating systems and weather patterns (Young 2017b; Kemp et al. 2005). Climate adaptation and mitigation goals must be integrated or mainstreamed into existing governance mechanisms around key land-use sectors such as forestry and agriculture. In the EU, mitigation has generally been well-mainstreamed in regional policies but not adaptation (Hanger et al. 2015). Climate change adaptation has been impeded by institutional barriers, including the inherent challenges of multi-level governance and policy integration (Biesbroek et al. 2010).

Integrative polycentric approaches to land use and climate interactions take different forms and operate with different institutions and governance mechanisms. Integrative approaches can provide coordination and linkages to improve effectiveness and efficiency and minimise conflicts (*high confidence*). Different types of integration with special relevance for the land–climate interface can be characterised as follows:

1. **Cross-level integration:** local and national level efforts must be coordinated with national and regional policies and also be capable of drawing direction and financing from global regimes, thus requiring multi-level governance. Integration of SLM to prevent, reduce and restore degraded land is advanced with national and subnational policy, including passing the necessary laws to establish frameworks and provide financial incentives. Examples include: integrated territorial planning addressing specific land-use decisions; local landscape participatory planning with farmer associations, microenterprises, and local institutions identifying hot spot areas, identifying land-use pressures and scaling out SLM response options (Liniger et al. 2019).
2. **Cross-sectoral integration:** rather than approach each application or sector (e.g., energy, agriculture, forestry) separately, there is a conscious effort at co-management and coordination in policies and institutions, such as with the energy–water–food nexus (Biggs et al. 2015).
3. **End-use/market integration:** often involves exploiting economies of scope across products, supply chains, and infrastructure (Nuhoff-Isakhanyan et al. 2016; Ashkenazy et al. 2017). For instance, land-use transport models consider land use, transportation, city planning, and climate mitigation (Ford et al. 2018).
4. **Landscape integration:** rather than physical separation of activities (e.g., agriculture, forestry, grazing), uses are spatially integrated by exploiting natural variations while incorporating local and regional economies (Harvey et al. 2014a). In an assessment of 166 initiatives in 16 countries, integrated landscape initiatives were found to address the drivers of agriculture, ecosystem conservation, livelihood preservation and institutional coordination. However, such initiatives struggled to move from planning to implementation due to lack of government and financial support, and powerful stakeholders sidelining the agenda (Zanzanaini et al. 2017). Special care helps ensure that initiatives don't exacerbate socio-spatial inequalities across diverse developmental and environmental conditions (Anguelovski et al. 2016b). Integrated land-use planning, coordinated through multiple government levels, balances property rights, wildlife and forest conservation, encroachment of settlements and agricultural areas and can reduce conflict (*high confidence*) (Metternicht 2018). Land-use planning can also enhance management of areas prone to natural disasters, such as floods, and resolve issues of competing land uses and land tenure conflicts (Metternicht 2018).

Another way to analyse or characterise governance approaches or mechanisms might be according to a temporal scale with respect to relevant events – for example, those that may occur gradually versus abruptly (Cash et al. 2006). Desertification and land degradation are drawn-out processes that occur over many years, whereas extreme events are abrupt and require immediate attention. Similarly, the frequency of events might be of special interest – for example, events that occur periodically versus those that occur infrequently and/or irregularly. In the case of food security, abrupt and protracted events of food insecurity might occur. There is a distinction between 'hunger months' and longer-term food insecurity. Some indigenous practices already incorporate hunger months whereas structural food deficits have to be addressed differently (Bacon et al. 2014). Governance mechanisms that facilitate rapid response to crises are quite different from those aimed at monitoring slower changes and responding with longer-term measures.

Case study | Governance: Biofuels and bioenergy

New policies and initiatives during the past decade or so have increased support for bioenergy as a non-intermittent (stored) renewable with wide geographic availability that is cost-effective in a range of applications. Significant upscaling of bioenergy requires dedicated (normally land-based) sources in addition to use of wastes and residues. As a result, a disadvantageous high land-use intensity compared to other renewables (Fritsche et al. 2017b) that, in turn, place greater demands on governance. Bioenergy, especially traditional fuels, currently provides the largest share of renewable energy globally and has a significant role in nearly all climate stabilisation scenarios, although estimates of its potential vary widely (see Cross-Chapter Box 7 in Chapter 6). Policies and governance for bioenergy systems and markets must address diverse applications and sectors across levels from local to global; here we briefly review the literature in relation to governance for modern bioenergy and biofuels with respect to land and climate impacts, whereas traditional biomass use (see Glossary) (> 50% of energy used today with greater land use and GHG emissions impacts in low- and medium-income countries (Bailis et al. 2015; Masera et al. 2015; Bailis et al. 2017a; Kiruki et al. 2017b)) is addressed elsewhere (Sections 4.5.4 and 7.4.6.4 and Cross-Chapter Box 12 in Chapter 7). The bioenergy lifecycle is relevant in accounting for – and attributing – land impacts and GHG emissions (Section 2.5.1.5). Integrated responses across different sectors can help to reduce negative impacts and promote sustainable development opportunities (Table 6.9, Table 6.58, Chapter 6).

Case study (continued)

It is very likely that bioenergy expansion at a scale that contributes significantly to global climate mitigation efforts (see Cross-Chapter Box 7 in Chapter 6) will result in substantial land-use change (Berndes et al. 2015; Popp et al. 2014a; Wilson et al. 2014; Behrman et al. 2015; Richards et al. 2017; Harris et al. 2015; Chen et al. 2017a). There is *medium evidence* and *high agreement* that land-use change at such scale presents a variety of positive and negative socio-economic and environmental impacts that lead to risks and trade-offs that must be managed or governed across different levels (Pahl-Wostl et al. 2018a; Kurian 2017; Franz et al. 2017; Chang et al. 2016; Larcom and van Gevelt 2017; Lubis et al. 2018; Alexander et al. 2015b; Rasul 2014; Bonsch et al. 2016; Karabulut et al. 2018; Mayor et al. 2015). There is *medium evidence* and *high agreement* that impacts vary considerably according to factors such as initial land-use type, choice of crops, initial carbon stocks, climatic region, soil types and the management regime and adopted technologies (Qin et al. 2016; Del Grosso et al. 2014; Popp et al. 2017; Davis et al. 2013; Mello et al. 2014; Hudiburg et al. 2015; Carvalho et al. 2016; Silva-Olaya et al. 2017; Whitaker et al. 2018; Alexander et al. 2015b).

There is *medium evidence* and *high agreement* that significant socio-economic impacts requiring additional policy responses can occur when agricultural lands and/or food crops are used for bioenergy, due to competition between food and fuel (Harvey and Pilgrim 2011; Rosillo Callé and Johnson 2010b), including impacts on food prices (Martin Persson 2015; Roberts and Schlenker 2013; Borychowski and Czyżewski 2015; Koizumi 2014; Muratori et al. 2016; Popp et al. 2014b; Araujo Enciso et al. 2016) and impacts on food security (Popp et al. 2014b; Bailey 2013; Pahl-Wostl et al. 2018b; Rulli et al. 2016; Yamagata et al. 2018; Kline et al. 2017; Schröder et al. 2018; Franz et al. 2017; Mohr et al. 2016). Additionally, crops such as sugarcane, which are water-intensive when used for ethanol production, have a trade-off with water and downstream ES and other crops more important for food security (Rulli et al. 2016; Gheewala et al. 2011). Alongside negative impacts that might fall on urban consumers (who purchase both food and energy), there is *medium evidence* and *medium agreement* that rural producers or farmers can increase income or strengthen livelihoods by diversifying into biofuel crops that have an established market (Maltsoglou et al. 2014; Mudombi et al. 2018a; Gasparatos et al. 2018a,b,c; von Maltitz et al. 2018; Kline et al. 2017; Rodríguez Morales and Rodríguez López 2017; Dale et al. 2015; Lee and Lazarus 2013; Rodríguez-Morales 2018). A key governance mechanism that has emerged in response to such concerns, (especially during the past decade) are standards and certification systems that include food security and land rights in addition to general criteria or indicators related to sustainable use of land and biomass (Section 7.4.6.3). There is *medium evidence* and *medium agreement* that policies promoting use of wastes and residues, use of non-edible crops and/or reliance on degraded and marginal lands for bioenergy could reduce land competition and associated risk for food security (Manning et al. 2015; Maltsoglou et al. 2014; Zhang et al. 2018a; Gu and Wylie 2017; Kline et al. 2017; Schröder et al. 2018; Suckall et al. 2015; Popp et al. 2014a; Lal 2013).

There is *medium evidence* and *high agreement* that good governance, including policy coherence and coordination across the different sectors involved (agriculture, forestry, livestock, energy, transport) (Section 7.6.2) can help to reduce the risks and increase the co-benefits of bioenergy expansion (Makkonen et al. 2015; Di Gregorio et al. 2017; Schut et al. 2013; Mukhtarov et al.; Torvanger 2019a; Müller et al. 2015; Nkonya et al. 2015; Johnson and Silveira 2014; Lundmark et al. 2014; Schultz et al. 2015; Silveira and Johnson 2016; Giessen et al. 2016b; Stattman et al. 2018b; Bennich et al. 2017b). There is *medium evidence* and *high agreement* that the nexus approach can help to address interconnected biomass resource management challenges and entrenched economic interests, and leverage synergies in the systemic governance of risk. (Bizikova et al. 2013; Rouillard et al. 2017; Pahl-Wostl 2017a; Lele et al. 2013; Rodríguez Morales and Rodríguez López 2017; Larcom and van Gevelt 2017; Pahl-Wostl et al. 2018a; Rulli et al. 2016; Rasul and Sharma 2016; Weitz et al. 2017b; Karlberg et al. 2015).

A key issue for governance of biofuels and bioenergy, as well as land-use governance more generally, during the past decade is the need for new governance mechanisms across different levels as land-use policies and bioenergy investments are scaled up and result in wider impacts (Section 7.6). There is *low evidence* and *medium agreement* that hybrid governance mechanisms can promote sustainable bioenergy investments and land-use pathways. This hybrid governance can include multi-level, transnational governance, and private-led or partnership-style (polycentric) governance, complementing national-level, strong public coordination (government and public administration) (Section 7.6.2) (Pahl-Wostl 2017a; Pacheco et al. 2016; Winickoff and Mondou 2017; Nagendra and Ostrom 2012; Jordan et al. 2015a; Djalante et al. 2013; Purkus, A, Gawel, E. and Thrän, D. 2012; Purkus et al. 2018; Stattman et al.; Rietig 2018; Cavicchi et al. 2017; Stupak et al. 2016; Stupak and Raulund-Rasmussen 2016; Westberg and Johnson 2013; Giessen et al. 2016b; Johnson and Silveira 2014; Stattman et al. 2018b; Mukhtarov et al.; Torvanger 2019b).

Cross-Chapter Box 12 | Traditional biomass use: Land, climate and development implications

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Introduction and significance

Most biomass used for energy today is in traditional forms (fuelwood, charcoal, agricultural residues) for cooking and heating by some 3 billion people worldwide (IEA 2017). Traditional biomass has high land and climate impacts, with significant harvesting losses, greenhouse gas (GHG) emissions, soil impacts and high conversion losses (Cutz et al. 2017b; Masera et al. 2015; Ghilardi et al. 2016a; Bailis et al. 2015; Fritsche et al. 2017b; Mudombi et al. 2018b). In addition to these impacts, indoor air pollution from household cooking is a leading cause of mortality in low- and medium-income countries and especially affects women and children (Smith et al. 2014a; HEI/IHME 2018; Goldemberg et al. 2018b). In rural areas, the significant time needed for gathering fuelwood imposes further costs on women and children (Njenga and Mendum 2018; Gurung and Oh 2013a; Behera et al. 2015a).

Both agricultural and woody biomass can be upgraded and used sustainably through improved resource management and modern conversion technologies, providing much greater energy output per unit of biomass (Cutz et al. 2017b; Hoffmann et al. 2015a; Gurung and Oh 2013b). More relevant than technical efficiency is the improved quality of energy services: with increasing income levels and/or access to technologies, households transition over time from agricultural residues and fuelwood to charcoal and then to gaseous or liquid fuels and electricity (Leach 1992; Pachauri and Jiang 2008; Goldemberg and Teixeira Coelho 2004; Smeets et al. 2012a). However, most households use multiple stoves and/or fuels at the same time, known as 'fuel stacking' for economic flexibility and also for socio-cultural reasons (Ruiz-Mercado and Masera 2015a; Cheng and Urpelainen 2014; Takama et al. 2012).

Urban and rural use of traditional biomass

In rural areas, fuelwood is often gathered at no cost to the user, and burned directly whereas, in urban areas, traditional biomass use may often involve semi-processed fuels, particularly in Sub-Saharan Africa where charcoal is the primary urban cooking fuel. Rapid urbanisation and/or commercialisation drives a shift from fuelwood to charcoal, which results in significantly higher wood use (*very high confidence*) due to losses in charcoal supply chains and the tendency to use whole trees for charcoal production (Santos et al. 2017; World Bank. 2009a; Hojas-Gascon et al. 2016a; Smeets et al. 2012b). One study in Myanmar found that charcoal required 23 times the land area of fuelwood (Win et al. 2018). In areas of woody biomass scarcity, animal dung and agricultural residues, as well as lower-quality wood, are often used (Kumar Nath et al. 2013a; Go et al. 2019a; Jagger and Kittner 2017; Behera et al. 2015b). The fraction of woody biomass harvested that is not 'demonstrably renewable' is the fraction of non-renewable biomass (fNRB) under UNFCCC accounting; default values for fNRB for least-developed countries and small island developing states ranged from 40–100% (CDM Executive Board 2012). Uncertainties in woodfuel data, complexities in spatiotemporal woodfuel modelling and rapid forest regrowth in some tropical regions present sources of variation in such estimates, and some fNRB values are *likely* to have been overestimated (McNicol et al. 2018a; Ghilardi et al. 2016b; Bailis et al. 2017b).

GHG emissions and traditional biomass

Due to over-harvesting, incomplete combustion and the effects of short-lived climate pollutants, traditional woodfuels (fuelwood and charcoal) contribute 1.9–2.3% of global GHG emissions; non-renewable biomass is concentrated especially in 'hotspot' regions of East Africa and South Asia (Bailis et al. 2015). The estimate only includes woody biomass and does not account for possible losses in soil carbon or the effects of nutrient losses from use of animal dung, which can be significant in some cases (Duguma et al. 2014a; Achat et al. 2015a; Sánchez et al. 2016). Reducing emissions of black carbon alongside GHG reductions offers immediate health co-benefits (Shindell et al. 2012; Pandey et al. 2017; Weyant et al. 2019a; Sparrevik et al. 2015). Significant GHG emissions reductions, depending on baseline or reference use, can be obtained through fuel-switching to gaseous and liquid fuels, sustainable harvesting of woodfuels, upgrading to efficient stoves, and adopting high-quality processed fuels such as wood pellets (*medium evidence*, *high agreement*) (Wathore et al. 2017; Jagger and Das 2018; Quinn et al. 2018; Cutz et al. 2017b; Carter et al. 2018; Bailis et al. 2015; Ghilardi et al. 2018; Weyant et al. 2019b; Hoffmann et al. 2015b).

Land and forest degradation

Land degradation is itself a significant source of GHG emissions and biodiversity loss, with over-harvesting of woodfuel as a major cause in some regions and especially in Sub-Saharan Africa (Pearson et al. 2017; Joana Specht et al. 2015a; Kiruki et al. 2017b; Ndegwa et al. 2016; McNicol et al. 2018b). Reliance on traditional biomass is quite land-intensive: supplying one household sustainably for a year can require more than half a hectare of land, which, in dryland countries such as Kenya, can result in substantial percentage of total tree cover (Fuso Nerini et al. 2017). In Sub-Saharan Africa and in some other regions, land degradation is widely associated with charcoal production (*high confidence*), often in combination with timber harvesting or clearing land for agriculture

Cross-Chapter Box 12 (continued)

(Kiruki et al. 2017a; Ndegwa et al. 2016; Hojas-Gascon et al. 2016b). Yet charcoal makes a significant contribution to livelihoods in many areas and thus, in spite of the ecological damage, halting charcoal production is difficult due to the lack of alternative livelihoods and/or the affordability of other fuels (Smith et al. 2015; Zulu and Richardson 2013a; Jones et al. 2016a; World Bank 2009b).

Use of agricultural residues and animal dung for bioenergy

Although agricultural wastes and residues from almost any crop can be used in many cases for bioenergy, excessive removal or reduction of forest (or agricultural) biomass can contribute to a loss of soil carbon, which can also, in turn, contribute to land degradation (James et al. 2016; Blanco-Canqui and Lal 2009a; Carvalho et al. 2016; Achat et al. 2015b; Stavi and Lal 2015). Removals are limited to levels at which problems of soil erosion, depletion of soil organic matter, soil nutrient depletion and decline in crop yield are effectively mitigated (Ayamga et al. 2015a; Baudron et al. 2014; Blanco-Canqui and Lal 2009b). Application or recycling of residues may, in some cases, be more valuable for soil improvement (*medium confidence*). Tao et al. (2017) used leftover oil palm fruit bunches and demonstrated that application of 30 to 90 t ha^{-1} empty fruit bunches maintains high palm oil yield with low temporal variability. A wide variety of wastes from palm oil harvesting can be used for bioenergy, including annual crop residues (Go et al. 2019b; Ayamga et al. 2015b; Gardner et al. 2018b).

Animal dung is a low-quality fuel used where woody biomass is scarce, such as in South Asia and some areas of eastern Africa (Duguma et al. 2014b; Behera et al. 2015b; Kumar Nath et al. 2013b). Carbon and nutrient losses can be significant when animal dung is dried and burned as cake, whereas using dung in a biodigester provides high-quality fuel and preserves nutrients in the by-product slurry (Clemens et al. 2018; Gurung and Oh 2013b; Quinn et al. 2018).

Production and use of biochar

Converting agricultural residues into biochar can also help to reverse trends of soil degradation (Section 4.10.7). The positive effects of using biochar have been demonstrated in terms of soil aggregate improvement, increase of exchangeable cations, cation exchange capacity, available phosphorus, soil pH and carbon sequestration as well as increased crop yields (Huang et al. 2018; El-Naggar et al. 2018; Wang et al. 2018; Oladele et al. 2019; Blanco-Canqui and Lal 2009b). The level of biochar effectiveness varies depending on the kind of feedstock, soil properties and rate of application (Shaaban et al. 2018; Pokharel and Chang 2019). In addition to adding value to an energy product, the use of biochar offers a climate-smart approach to addressing agricultural productivity (Solomon and Lehmann 2017).

Relationship to food security and other Sustainable Development Goals (SDGs)

The population that is food insecure also intersects significantly with those relying heavily on traditional biomass such that poor and vulnerable populations often expend considerable time (gathering fuel) or use a significant share of household income for low-quality energy services (Fuso Nerini et al. 2017; McCollum et al. 2018; Rao and Pachauri 2017; Pachauri et al. 2018; Muller and Yan 2018; Takama et al. 2012). Improvements in energy access and reduction or elimination of traditional biomass use thus have benefits across multiple SDGs (*medium evidence*, *high agreement*) (Masera et al. 2015; Rao and Pachauri 2017; Pachauri et al. 2018; Hoffmann et al. 2017; Jeuland et al. 2015; Takama et al. 2012; Gitau et al. 2019; Quinn et al. 2018; Ruiz-Mercado and Masera 2015b; Duguma et al. 2014b; Sola et al. 2016b). Improved energy access contributes to adaptive capacity, although charcoal production itself can also serve as a diversification or adaptation strategy (Perera et al. 2015; Ochieng et al. 2014; Sumiya 2016; Suckall et al. 2015; Jones et al. 2016b).

Socio-economic choices and shifts

When confronted with the limitations of higher-priced household energy alternatives, climate mitigation policies can result in trade-offs with health, energy access and other SDGs (Cameron et al. 2016; Fuso Nerini et al. 2018). The poorest households have no margin to pay for higher-cost efficient stoves; a focus on product-specific characteristics, user needs and/or making clean options more available would improve the market take-up (*medium confidence*) (Takama et al. 2012; Mudombi et al. 2018c; Khandelwal et al. 2017; Rosenthal et al. 2017; Cundale et al. 2017; Jürisoo et al. 2018). Subsidies for more efficient end-use technologies, in combination with promotion of sustainable harvesting techniques, would provide the highest emissions reductions while improving energy services (Cutz et al. 2017a).

Knowledge gaps

Unlike analyses on modern energy sources, scientific assessments on traditional biomass use are complicated by its informal nature and the difficulty of tracing data and impacts; more systematic analytical efforts are needed to address this research gap

Cross-Chapter Box 12 (continued)

(Cerutti et al. 2015). In general, traditional biomass use is associated with poverty. Therefore, efforts to reduce the dependence on fuelwood use are to be conducted in coherence with poverty alleviation (McCollum et al. 2018; Joana Specht et al. 2015b; Zulu and Richardson 2013b). The substantial potential co-benefits suggest that the traditional biomass sector remains under-researched and under-exploited in terms of cost-effective emissions reductions, as well as for synergies between climate stabilisation goals and other SDGs.

7.6.3 Adaptive climate governance responding to uncertainty

In the 1990s, adaptive governance emerged from adaptive management (Holling 1978, 1986), combining resilience and complexity theory, and reflecting the trend of moving from government to governance (Hurlbert 2018b). Adaptive governance builds on multi-level and polycentric governance. Adaptive governance is 'a process of resolving trade-offs and charting a course for sustainability' (Boyle et al. 2001, p. 28) through a range of 'political, social, economic and administrative systems that develop, manage and distribute a resource in a manner promoting resilience through collaborative, flexible and learning-based issue management across different scales' (Hurlbert 2018, p. 25). There is *medium evidence* and *medium agreement* that few alternative governance theories handle processes of change characterised by nonlinear dynamics, threshold effects, cascades and limited predictability; however, the majority of literature relates to the USA or Canada (Karpouzoglou et al. 2016). Combining adaptive governance with other theories has allowed good evaluation of important governance features such as power and politics, inclusion and equity, short-term and long-term change, and the relationship between public policy and adaptive governance (Karpouzoglou et al. 2016).

There is *robust evidence* and *high agreement* that resource and disaster crises are crises of governance (Pahl-Wostl 2017b; Villagra and Quintana 2017; Gupta et al. 2013b). Adaptive governance of risk has emerged in response to these crises and involves four critical pillars (Fra.Paleo 2015):

1. Sustainability as a response to environmental degradation, resource depletion and ES deterioration
2. Recognition that governance is required as government is unable to resolve key societal and environmental problems, including climate change and complex problems
3. Mitigation as a means to reduce vulnerability and avoid exposure
4. Adaptation responds to changes in environmental conditions.

Closely related to (and arguably components of) adaptive governance are adaptive management (Section 7.5.4) (a regulatory environment that manages ecological system boundaries through hypothesis testing, monitoring, and re-evaluation (Mostert et al. 2007)), adaptive co-management (flexible community-based resource management (Plummer and Baird 2013)), and anticipatory governance (flexible decision-making through the use of scenario planning and reiterative policy review (Boyd et al. 2015)). Adaptive governance can be conceptualised as including multilevel governance with a balance between top-down and bottom-up decision-making that is performed by many actors (including citizens) in both formal and informal networks, allowing policy measures and governance arrangements to be tailored to local context and matched at the appropriate scale of the problem, allowing for opportunities for experimentation and learning by individuals and social groups (Rouillard et al. 2013; Hurlbert 2018b).

There is *high confidence* that anticipation is a key component of adaptive climate governance wherein steering mechanisms in the present are developed to adapt to and/or shape uncertain futures (Vervoort and Gupta 2018; Wiebe et al. 2018; Fuerth 2009). Effecting this anticipatory governance involves simultaneously making short-term decisions in the context of longer-term policy visioning, anticipating future climate change models and scenarios in order to realise a more sustainable future (Bates and Saint-Pierre 2018; Serrao-Neumann et al. 2013; Boyd et al. 2015). Utilising the decision-making tools and practices in Section 7.5, policymakers operationalise anticipatory governance through a foresight system considering future scenarios and models, a networked system for integrating this knowledge into the policy process, a feedback system using indicators (Section 7.5.5) to gauge performance, an open-minded institutional culture allowing for hybrid and polycentric governance (Fuerth and Faber 2013; Fuerth 2009).

There is *high confidence* that, in order to manage uncertainty, natural resource governance systems need to allow agencies and stakeholders to learn and change over time, responding to ecosystem changes and new information with different management strategies and practices that involve experimentation (Camacho 2009; Young 2017b). There is emerging literature on experimentation in governance surrounding climate change and land use (Kivimaa et al. 2017a) including policies such as REDD+ (Kaisa et al. 2017). Governance experiment literature could be in relation to scaling up policies from the local level for greater application, or downscaling policies addressing broad complex issues such as climate change, or addressing necessary change in social processes across sectors (such as water energy and food) (Laakso et al. 2017). Successful development of new policy instruments occurred in a governance experiment relating to coastal policy adapting to rising sea levels and extreme weather events through planned retreat (Rocle and Salles 2018). Experiments in emissions trading between 1968 and 2000 in the USA helped to realise specific models of governance and material practices through mutually supportive lab experiments and field applications that advanced collective knowledge (Voß and Simons 2018).

There is *high confidence* that an SLM plan is dynamic and adaptive over time to (unforeseen) future conditions by monitoring indicators as early warnings or signals of tipping points, initiating a process of change in policy pathway before a harmful threshold is reached (Stephens et al. 2018, 2017; Haasnoot et al. 2013; Bloemen et al. 2018) (Section 7.5.2.2). This process has been applied in relation to coastal sea level rise, starting with low-risk, low-cost measures and working up to measures requiring greater investment after review and reevaluation (Barnett et al. 2014). A first measure was stringent controls of new development, graduating to managed relocation of low-lying critical infrastructure, and eventually movement of habitable dwellings to more elevated parts of town, as flooding and inundation triggers are experienced (Haasnoot et al. 2018; Lawrence et al. 2018; Barnett et al. 2014; Stephens et al. 2018). Nanda et al. (2018) apply the concept to a wetland in Australia to identify a mix of short- and long-term decisions, and Prober et al. (2017) develop adaptation pathways for agricultural landscapes, also in Australia. Both studies identify that longer-term decisions may involve a considerable change to institutional arrangements at different scales. Viewing climate mitigation as a series of connected decisions over a long time period and not an isolated decision, reduces the fragmentation and uncertainty endemic of models and effectiveness of policy measures (Roelich and Giesekam 2019).

There is *medium evidence* and *high agreement* that participatory processes in adaptive governance within and across policy regimes overcome limitations of polycentric governance, allowing priorities to be set in sustainable development through rural land management and integrated water resource management (Rouillard et al. 2013). Adaptive governance addresses large uncertainties and their social amplification through differing perceptions of risk (Kasperson 2012; Fra.Paleo 2015) offering an approach to co-evolve with risk by implementing policy mixes and assessing effectiveness in an ongoing process, making mid-point corrections when necessary (Fra.Paleo 2015). In respect of climate adaptation to coastal and riverine land erosion due to extreme weather events impacting on communities, adaptive governance offers the capacity to monitor local socio-economic processes and implement dynamic locally informed institutional responses. In Alaska, adaptive governance responded to the dynamic risk of extreme weather events and issue of climate migration by providing a continuum of policy from protection in place to community relocation, integrating across levels and actors in a more effective and less costly response option than other governance systems (Bronen and Chapin 2013). In comparison to other governance initiatives of ecosystem management aimed at conservation and sustainable use of natural capital, adaptive governance has visible effects on natural capital by monitoring, communicating and responding to ecosystem-wide changes at the landscape level (Schultz et al. 2015). Adaptive governance can be applied to manage drought assistance as a common property resource. Adaptive governance can manage complex, interacting goals to create innovative policy options, facilitated through nested and polycentric systems of governance, effected by watershed or catchment management groups in areas of natural resource management (Nelson et al. 2008).

There is *medium evidence* and *high agreement* that transformational change is a necessary societal response option to manage climate risks which is uniquely characterised by the depth of change needed to reframe problems and change dominant mindsets, the scope of change needed (that is larger than just a few people) and the speed of change required to reduce emissions (O'Brien et al. 2012; Termeer et al. 2017). Transformation of governance occurs with changes in values to reflect an understanding that the environmental crisis occurs in the context of our relation with the earth (Hordijk et al. 2014; Pelling 2010). Transformation can happen by intervention strategies that enable small in-depth wins, amplify these small wins through integration into existing practices, and unblock stagnations (locked in structures) preventing transformation by confronting social and cognitive fixations with counterintuitive interventions (Termeer et al. 2017). Iterative consideration of issues and reformulation of policy instruments and response options facilitates transformation by allowing experimentation (Monkelbaan 2019).

Box 7.2 | Adaptive governance and interlinkages of food, fibre, water, energy and land

Emerging literature and case studies recognise the connectedness of the environment and human activities, and the interrelationships of multiple resource-use practices in an attempt to understand synergies and trade-offs (Albrecht et al. 2018). Sustainable adaptation – or actions contributing to environmentally and socially sustainable development pathways (Eriksen et al. 2011) – requires consideration of the interlinkage of different sectors (Rasul and Sharma 2016). Integrating considerations can address sustainability (Hoff 2011) showing promise (Allan et al. 2015) for effective adaptation to climate impacts in many drylands (Rasul and Sharma 2016).

Case studies of integrated water resources management (IWRM), landscape- and ecosystem-based approaches illustrate important dimensions of institutions, institutional coordination, resource coupling and local and global connections (Scott et al. 2011). Integrated governance, policy coherence, and use of multi-functional systems are required to advance synergies across land, water, energy and food sectors (Liu et al. 2017).

Case study: Flood and food security

Between 2003 and 2013, floods were the natural disaster that most impacted on crop production (FAO 2015b) (albeit in certain contexts, such as riverine ecosystems and flood plain communities, floods can be beneficial).

Box 7.2 (continued)

In developing countries, flood jeopardises primary access to food and impacts on livelihoods. In Bangladesh, the 2007 flood reduced average consumption by 103Kcal/cap/day (worsening the existing 19.4% calories deficit), and in Pakistan, the 2010 flood resulted in a loss of 205 Kcal/cap/day (or 8.5% of the Pakistan average food supply). The 2010 flood affected more than 4.5 million workers, two-thirds employed in agriculture; and 79% of farms lost greater than one-half of their expected income (Pacetti et al. 2017).

Policy instruments and responses react to the sequential and cascading impacts of flood. In a Malawi study, flood impacts cascaded through labour, trade and transfer systems. First a harvest failure occurred, followed by the decline of employment opportunities and reduction in real wages, followed by a market failure or decline in trade, ultimately followed by a failure in informal safety nets (Devereux 2007). Planned policy responses include those that address the sequential nature of the cascading impacts, starting with 'productivity-enhancing safety nets' addressing harvest failure, then public works programmes addressing the decline in employment opportunities, followed by food price subsidies to address the market failure, and finally food aid to address the failure of informal safety nets (Devereux 2007). In another example in East Africa's range lands, flood halted livestock sales, food prices fell, and grain production ceased. Local food shortages couldn't be supplemented with imports due to destruction of transport links, and pastoral incomes were inadequate to purchase food. Livestock diseases became rampant and eventually food shortages led to escalating prices. Due to the contextual nature and timing of events, policy responses initially addressed mobility and resource access, and eventually longer-term issues such as livestock disease (Little et al. 2001).

In North America, floods are often described in terms of costs. For instance, the 1997 Red River Basin flood cost Manitoba, Canada 1 billion USD and the USA 4 billion USD in terms of impact on agriculture and food production (Adaptation to Climate Change Team 2013). In Canada, floods accounted for 82% of disaster financial assistance spent from 2005–2014 (Public Safety Canada 2017) and this cost may increase in the future. Future climate change may result in a 2 meter in sea level by 2100, costing from 507 to 882 billion USD, affecting 300 American cities (losing one-half of their homes) and the wholesale loss of 36 cities (Lemann 2018).

Policy measures are important as an increasingly warming world may make post-disaster assistance and insurance increasingly unaffordable (Surminski et al. 2016). Historic legal mechanisms for retreating from low-lying and coastal areas have failed to encourage relocation of people out of flood plains and areas of high risk (Stoa 2015). In some places, cheap flood insurance and massive aid programmes have encouraged the populating of low-lying flood-prone and coastal areas (Lemann 2018). Although the state makes disaster assistance payments, it is local governments that determine vulnerability through flood zone mapping, restrictions from building in flood zones, building requirements (Stoa 2015), and integrated planning for flood. A comprehensive policy mix (Section 7.4.8) (implemented through adaptive management as illustrated in Figure 7.6) reduces vulnerability (Hurlbert 2018a,b). Policy mixes that allow people to respond to disasters include bankruptcy, insolvency rules, house protected from creditors, income minimums, and basic agricultural implement protection laws. The portfolio of policies allows people to recover and, if necessary, migrate to other areas and occupations (Hurlbert 2018b).

At the international level, reactionary disaster response has evolved to proactive risk management that combines adaptation and mitigation responses to ensure effective risk response, build resilient systems and solve issues of structural social inequality (Innocenti and Albrito 2011). Advanced measures of preparedness are the main instruments to reduce fatalities and limit damage, as illustrated in Figure 7.8. The Sendai Declaration (Sendai Framework for Disaster Risk Reduction 2015–2030), is an action plan to reduce mortality, the number of affected people and economic losses, using four priorities: understanding disaster risk; strengthening its governance to enhance the ability to manage disaster risk; investing in resilience; and enhancing disaster preparedness. There is *medium evidence* and *high agreement* that the Sendai Declaration significantly refers to adaptive governance and could be a window of opportunity to transform disaster risk reduction to address the causes of vulnerability (Munene et al. 2018). Addressing disasters increasingly requires individual, household, community and national planning and commitment to a new path of resilience and shared responsibility through whole community engagement and linking private and public infrastructure interests (Rouillard et al. 2013). It is recommended that a vision and overarching framework of governance be adopted to allow participation and coordination by government, NGOs, researchers and the private sector, individuals in the neighbourhood community. Disaster risk response is enhanced with complementary structural and non-structural measures, implemented together with measurable scorecard indicators (Chen 2011).

Box 7.2 (continued)

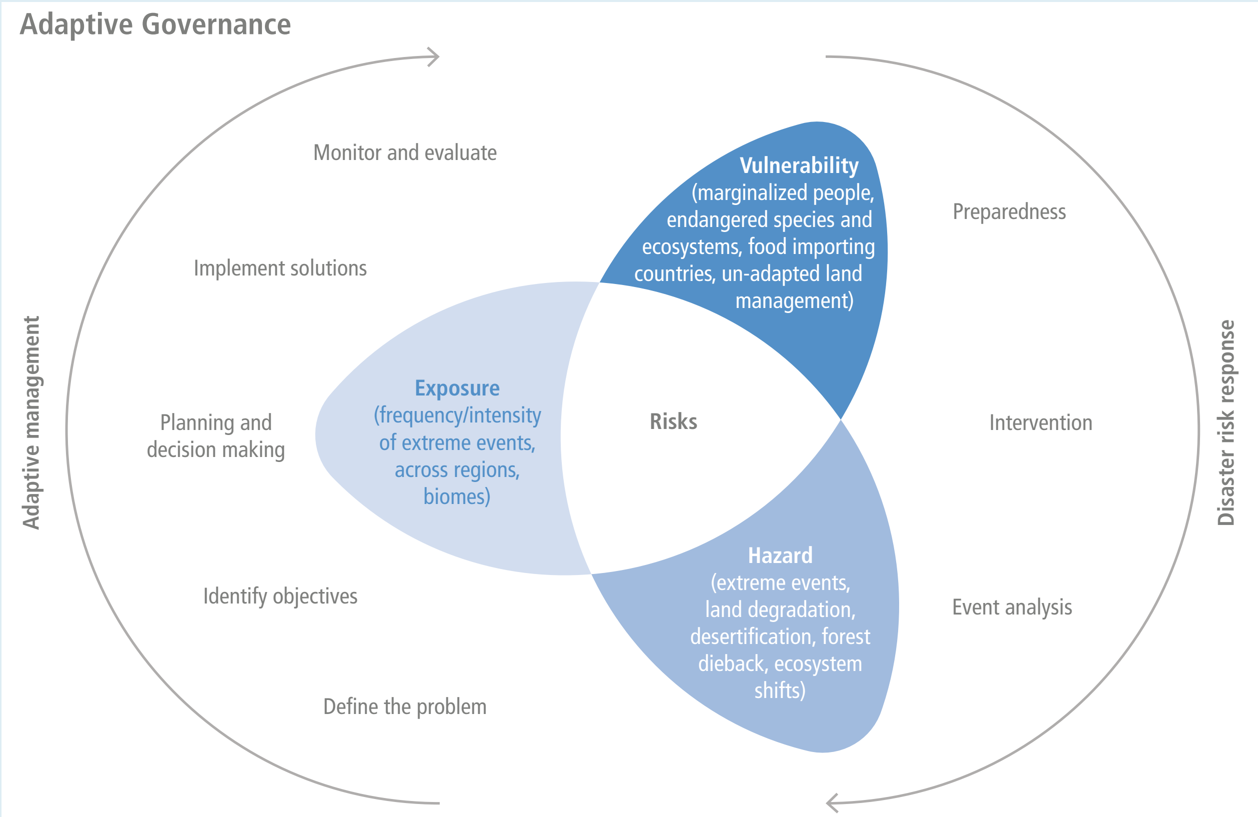

Figure 7.8 | Adaptive governance.

Adaptive management identifies and responds to exposure and vulnerability to land and climate change impacts by identifying problems and objectives, making decisions in relation to response options, and instruments advancing response options in the context of uncertainty. These decisions are continuously monitored, evaluated and adjusted to changing conditions. Similarly disaster risk management responds to hazards through preparation, prevention, response, analysis, and reconstruction in an iterative process.

7.6.4 Participation

It is recognised that more benefits are derived when citizens actively participate in land and climate decision-making, conservation, and policy formation (*high confidence*) (Jansujwicz et al. 2013; Coenen and Coenen 2009; Hurlbert and Gupta 2015). Local leaders supported by strong laws, institutions, and collaborative platforms, are able to draw on local knowledge, challenge external scientists, and find transparent and effective solutions for climate and land conflicts (Couvet and Prevot 2015; Johnson et al. 2017). Meaningful participation is more than providing technical/scientific information to citizens in order to accept decisions already made – rather, it allows citizens to deliberate about climate change impacts to determine shared responsibilities, creating genuine opportunity to construct, discuss and promote alternatives (*high confidence*) (Lee et al. 2013; Armeni 2016; Pieraccini 2015; Serrao-Neumann et al. 2015b; Armeni 2016). Participation is an emerging quality of collective action and social learning processes (Castella et al. 2014) when barriers for meaningful participation are surpassed (Clemens et al. 2015). The absence of systematic leadership, the lack of consensus on the place of direct citizen participation, and the limited scope and powers of participatory innovations, limits the utility of participation (Fung 2015).

Multiple methods of participation exist, including multi-stakeholder forums, participatory scenario analyses, public forums and citizen juries (Coenen and Coenen 2009). No one method is superior, but each method must be tailored for local context (*high confidence*) (Blue and Medlock 2014; Voß and Amelung 2016). Strategic innovation in developing policy initiatives requires a strategic adaptation framework involving pluralistic and adaptive processes and use of boundary organisations (Head 2014).

The framing of a land and climate issue can influence the manner of public engagement (Hurlbert and Gupta 2015) and studies have found that local frames of climate change are particularly important (Hornsey et al. 2016; Spence et al. 2012), emphasising diversity of perceptions to adaptation and mitigation options (Capstick et al. 2015) – although Singh and Swanson (2017) found little evidence that framing impacted on the perceived importance of climate change.

Recognition and use of indigenous and local knowledge (ILK) is an important element of participatory approaches of various kinds. ILK can be used in decision-making on climate change adaptation, SLM and food security at various scales and levels, and is important for long-term sustainability (*high confidence*). Cross-Chapter Box 13 discusses definitional issues associated with ILK, evidence of its usefulness in responses to land-climate challenges, constraints on its use, and possibilities for its incorporation in decision-making.

Cross-Chapter Box 13 | Indigenous and local knowledge (ILK)

John Morton (United Kingdom), Fatima Denton (The Gambia), James Ford (United Kingdom), Joyce Kimutai (Kenya), Pamela McElwee (The United States of America), Marta Rivera Ferre (Spain), Lindsay Stringer (United Kingdom).

Indigenous and local knowledge (ILK) can play a key role in climate change adaptation (*high confidence*) (Mapfumo et al. 2017; Nyong et al. 2007; Green and Raygorodetsky 2010; Speranza et al. 2010; Alexander et al. 2011; Leonard et al. 2013; Nakashima et al. 2013; Tschakert 2007). The Summary for Policymakers of the Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014b, p. 26) states that 'Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation' (see also Ford et al. 2016). The IPCC's Special Report on Global Warming of 1.5°C (SR15) (IPCC 2018a; de Coninck et al. 2018) confirms the effectiveness and potential feasibility of adaptation options based on ILK, but also raises concerns that such knowledge systems are being threatened by multiple socio-economic and environmental drivers (*high confidence*). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Land Degradation and Restoration Assessment (IPBES 2018) finds the same – that ILK can support adaptation to land degradation, but is threatened.

A variety of terminology has been used to describe ILK: indigenous knowledge, local knowledge, traditional knowledge, traditional ecological knowledge, and other terms are used in overlapping and often inconsistent ways (Naess 2013). SR15 (IPCC 2018a) reserves 'indigenous knowledge' for culturally distinctive ways of knowing associated with 'societies with long histories of interaction with their natural surroundings', while using 'local knowledge' for 'understandings and skills developed by individuals and populations, specific to the places where they live', but not all research studies observe this distinction. This Special Report generally uses ILK as a combined term for these forms of knowledge, but in some sections the terminology used follows that from the research literature assessed.

In contrast to scientific knowledge, ILK is context-specific, collective, transmitted informally, and is multi-functional (Mistry and Berardi 2016; Naess 2013; Janif et al. 2016). Persson et al. (2018) characterise ILK as 'practical experience', as locally held knowledges are acquired through processes of experience and interaction with the surrounding physical world. ILK is embedded in local institutions (Naess 2013) and in cultural aspects of landscape and food systems (Fuller and Qingwen 2013; Koohafkan and Altieri 2011). ILK can encompass such diverse content as factual information about the environment, guidance on rights and management, value statements about interactions with others, and cosmologies and worldviews that influence how information is perceived and acted on, among other topics (Spoon 2014; Usher 2000).

This cross-chapter box assesses evidence for the positive role of ILK in understanding climate change and other environmental processes, and in managing land sustainably in the face of climate change, desertification, land degradation and food insecurity. It also assesses constraints on and threats to the use of ILK in these challenges, and processes by which ILK can be incorporated in decision-making and governance processes.

ILK in understanding and responding to climate change impacts

ILK can play a role in understanding climate change and other environmental processes, particularly where formal data collection is sparse (Alexander et al. 2011; Schick et al. 2018), and can contribute to accurate predictions of impending environmental change (Green and Raygorodetsky 2010; Orlove et al. 2010) (*medium confidence*). At both global level (Alexander et al. 2011; Green and Raygorodetsky 2010), and local level (Speranza et al. 2010; Ayanlade et al. 2017), strong correlations between local perceptions of climate change and meteorological data have been shown, as calendars, almanacs, and other seasonal and interannual systems knowledge embedded in ILK hold information about environmental baselines (Orlove et al. 2010; Cochran et al. 2016).

Cross-Chapter Box 13 (continued)

ILK is strongly associated with sustainable management of natural resources, (including land), and with autonomous adaptation to climate variability and change, while also serving as a resource for externally-facilitated adaptation (Stringer et al. 2009). For example, women's traditional knowledge adds value to a society's knowledge base and supports climate change adaptation practices (Lane and McNaught 2009). In dryland environments, populations have historically demonstrated remarkable resilience and innovation to cope with high climatic variability, manage dynamic interactions between local communities and ecosystems, and sustain livelihoods (Safriel and Adeel 2008; Davies 2017). There is *high confidence* that pastoralists have created formal and informal institutions based on ILK for regulating grazing, collection and cutting of herbs and wood, and use of forests across the Middle East and North Africa (Louhaichi and Tastad 2010; Domínguez 2014; Auclair et al. 2011), Mongolia (Fernandez-Gimenez 2000), the Horn of Africa (Oba 2013) and the Sahel (Krätli and Schareika 2010). Herders in both the Horn of Africa and the Sahel have developed complex livestock breeding and selection systems for their dryland environment (Krätli 2008; Fre 2018). Numerous traditional water harvesting techniques are used across the drylands to adapt to climate variability: planting pits (*zai, ngoro*) and micro-basins and contouring hill slopes and terracing (Biazin et al. 2012), alongside the traditional *ndiva* water harvesting system in Tanzania to capture runoff in community-managed micro-dams for small-scale irrigation (Enfors and Gordon 2008).

Across diverse agro-ecological systems, ILK is the basis for traditional practices to manage the landscape and sustain food production, while delivering co-benefits in the form of biodiversity and ecosystem resilience at a landscape scale (*high confidence*). Flexibility and adaptiveness are hallmarks of such systems (Richards 1985a; Biggs et al. 2013), and documented examples include: traditional integrated watershed management in the Philippines (Camacho et al. 2016); widespread use of terracing, with benefits, in cases of both intensifying and decreasing rainfall (Arnáez et al. 2015; Chen et al. 2017b) and management of water harvesting and local irrigation systems in the Indo-Gangetic Plains (Rivera-Ferre et al. 2016). Rice cultivation in East Borneo is sustained by traditional forms of shifting cultivation, often involving intercropping of rice with bananas, cassava and other food crops (Siahaya et al. 2016), although the use of fire in land clearance implies trade-offs for climate change mitigation which have been sparsely assessed. Indigenous practices for enhanced soil fertility have been documented among South Asian farmers (Chandra et al. 2011; Dey and Sarkar 2011) and among Mayan farmers, where management of carbon has positive impacts on mitigation (Falkowski et al. 2016). Korean traditional groves or 'bibosoop' have been shown to reduce wind speed and evaporation in agricultural landscapes (Koh et al. 2010). Particularly in the context of changing climates, agriculture based on ILK that focuses on biodiversification, soil management, and sustainable water harvesting holds promise for long-term resilience (Altieri and Nicholls 2017) and rehabilitation of degraded land (Maikhuri et al. 1997). ILK is also important in other forms of ecosystem management, such as forests and wetlands, which may be conserved by efforts such as sacred sites (Ens et al. 2015; Pungetti et al. 2012). ILK can also play an important role in ecological restoration efforts, including for carbon sinks, through knowledge surrounding species selection and understanding of ecosystem processes, like fire (Kimmerer 2000).

Constraints on the use of ILK

Use of ILK as a resource in responding to climate change can be constrained in at least three ways (*high confidence*). First, the rate of climate change and the scale of its impacts may render incremental adaptation based on the ILK of smallholders and others, less relevant and less effective (Lane and McNaught 2009; Orlowsky and Seneviratne 2012; Huang et al. 2016; Morton 2017). Second, maintenance and transmission of ILK across generations may be disrupted, for example, by formal education, missionary activity, livelihood diversification away from agriculture, and a general perception that ILK is outdated and unfavourably contrasted with scientific knowledge (Speranza et al. 2010), and by HIV-related mortality (White and Morton 2005). Urbanisation can erode ILK, although ILK is constantly evolving, and becoming integrated into urban environments (Júnior et al. 2016; Oteros-Rozas et al. 2013; van Andel and Carvalheiro 2013). Third, ILK holders are experiencing difficulty in using ILK due to loss of access to resources, such as through large-scale land acquisition (Siahaya et al. 2016; Speranza et al. 2010; de Coninck et al. 2018). The increasing globalisation of food systems and integration into global market economy also threatens to erode ILK (Gómez-Baggethun et al. 2010; Oteros-Rozas et al. 2013; McCarter et al. 2014). The potential role that ILK can play in adaptation at the local level depends on the configuration of a policy–institutions–knowledge nexus (Stringer et al. 2018), which includes power relations across levels and interactions with government strategies (Alexander et al. 2011; Naess 2013).

Incorporation of ILK in decision-making

ILK can be used in decision-making on climate change adaptation, sustainable land management (SLM) and food security at various scales and levels, and is important for long-term sustainability (*high confidence*). Respect for ILK is both a requirement and an entry strategy for participatory climate action planning and effective communication of climate action strategies (Nyong et al. 2007). The nature, source, and mode of knowledge generation are critical to ensure that sustainable solutions are community-owned and fully integrated within the local context (Mistry and Berardi 2016). Integrating ILK with scientific information is a prerequisite for such community-owned solutions. Scientists can engage farmers as experts in processes of knowledge co-production (Oliver et al. 2012),

Cross-Chapter Box 13 (continued)

helping to introduce, implement, adapt and promote locally appropriate responses (Schwilch et al. 2011). Specific approaches to decision-making that aim to integrate indigenous and local knowledge include some versions of decision support systems (Jones et al. 2014) as well as citizen science and participatory modelling (Tengö et al. 2014).

ILK can be deployed in the practice of climate governance, especially at the local level where actions are informed by the principles of decentralisation and autonomy (Chanza and de Wit 2016; Harmsworth and Awatere 2013). International environmental agreements are also increasingly including attention to ILK and diverse cultural perspectives, for reasons of social justice and inclusive decision-making (Brondizio and Tourneau 2016). However, the context-specific, and dynamic nature of ILK and its embeddedness in local institutions and power relations needs consideration (Naess 2013). It is also important to take a gendered approach so as not to further marginalise certain knowledge, as men and women hold different knowledge, expertise and transmission patterns (Díaz-Reviriego et al. 2017).

Citizen science

Citizen science is a democratic approach to science involving citizens in collecting, classifying, and interpreting data to influence policy and assist decision processes, including issues relevant to the environment (Kullenberg and Kasperowski 2016). It has flourished in recent years due to easily available technical tools for collecting and disseminating information (e.g., cell phone-based apps, cloud-based services, ground sensors, drone imagery, and others), recognition of its free source of labour, and requirements of funding agencies for project-related outreach (Silvertown 2009). There is significant potential for combining citizen science and participatory modelling to obtain favourable outcomes and improve environmental decision-making (*medium confidence*) (Gray et al. 2017). Citizen participation in land-use simulation integrates stakeholders' preferences through the generation of parameters in analytical and discursive approaches (Hewitt et al. 2014), and thereby supports the translation of narrative scenarios to quantitative outputs (Mallampalli et al. 2016), supports the development of digital tools to be used in co-designing decision-making participatory structures (Bommel et al. 2014), and supports the use of games to understand the preferences of local decision-making when exploring various balanced policies about risks (Adam et al. 2016).

There is *medium confidence* that citizen science improves SLM through mediating and facilitating landscape conservation decision-making and planning, as well as boosting environmental awareness and advocacy (Lange and Hehl-Lange 2011; Bonsu et al. 2017; Graham et al. 2015; Bonsu et al. 2017; Lange and Hehl-Lange 2011; Sayer et al. 2015; McKinley et al. 2017; Johnson et al. 2017, 2014; Gray et al. 2017). One study found limited evidence of direct conservation impact (Ballard et al. 2017) and most of the cases derive from rich industrialised countries (Loos et al. 2015). There are many practical challenges to the concept of citizen science at the local level. These include differing methods and the lack of universal implementation framework (Conrad and Hilchey 2011; Jalbert and Kinchy 2016; Stone et al. 2014). Uncertainty related to citizen science needs to be recognised and managed (Swanson et al. 2016; Bird et al. 2014; Lin et al. 2015) and citizen science projects around the world need better coordination to understand significant issues, such as climate change (Bonney et al. 2014).

Participation, collective action, and social learning

As land and climate issues cannot be solved by one individual, a diverse collective action issue exists for land-use policies and planning practices (Moroni 2018) at local, national, and regional levels. Collective action involves individuals and communities in land-planning processes in order to determine successful climate adaptation and mitigation (Nkoana et al. 2017; Liu and Ravenscroft 2017; Nieto-Romero et al. 2016; Nikolakis et al. 2016), or as Sarzynski (2015) finds, a community 'pulling together' to solve common adaptation and land-planning issues.

Collective action offers solutions for emerging land and climate change risks, including strategies that target maintenance or change of land-use practices, increase livelihood security, share risk through pooling, and sometimes also aim to promote social and economic goals such as reducing poverty (Samaddar et al. 2015; Andersson and Gabrielsson 2012). Collective action has resulted in the successful implementation of national-level land transfer policies (Liu and Ravenscroft 2017), rural development and land sparing (Jelsma et al. 2017), and the development of tools to identify shared objectives, trade-offs and barriers to land management (Nieto-Romero et al. 2016; Nikolakis et al. 2016). Collective action can also produce mutually binding agreements, government regulation, privatisation, and incentive systems (IPCC 2014c).

Successful collective action requires understanding and implementation of factors that determine successful participation in climate adaptation and mitigation (Nkoana et al. 2017). These include ownership, empowerment or self-reliance, time effectiveness, economic and behavioural interests, livelihood security, and the requirement for plan implementation (Samaddar et al. 2015; Djurfeldt et al. 2018; Sánchez and Maseda 2016). In a UK study, dynamic trust relations among members around specific issues, determined the potential of agri-environmental schemes to offer landscape-scale environmental protection (Riley et al. 2018). Collective action is context specific and rarely scaled up or replicated in other places (Samaddar et al. 2015).

Collective action in land-use policy has been shown to be more effective when implemented as bundles of actions rather than as single-issue actions. For example, land tenure, food security, and market access can mutually reinforce each other when they are interconnected (Corsi et al. 2017). For example, Liu and Ravenscroft (2017) found that financial incentives embedded in collective forest reforms in China have increased forest land and labour inputs in forestry.

A product of participation, equally important in practical terms, is social learning (*high confidence*) (Reed et al. 2010; Dryzek and Pickering 2017; Gupta 2014), which is learning in and with social groups through interaction (Argyris 1999) including collaboration and organisation which occurs in networks of interdependent stakeholders (Mostert et al. 2007). Social learning is defined as a change in understanding measured by a change in behaviour, and perhaps worldview, by individuals and wider social units, communities of practice and social networks (Reed et al. 2010; Gupta 2014). Social learning is an important factor contributing to long-term climate adaptation whereby individuals and organisations engage in a multi-step social process, managing different framings of issues while raising awareness of climate and land risks and opportunities, exploring policy options and institutionalising new rights, responsibilities, feedback and learning processes (Tàbara et al. 2010). It is important for engaging with uncertainty (Newig et al. 2010) and addressing the increasing unequal geography of food security (Sonnino et al. 2014).

Social learning is achieved through reflexivity or the ability of a social structure, process, or set of ideas to reconfigure itself after reflection on performance through open-minded people interacting iteratively to produce reasonable and well-informed opinions (Dryzek and Pickering 2017). These processes develop through skilled facilitation attending to social differences and power, resulting in a shared view of how change might happen (Harvey et al. 2012; Ensor and Harvey 2015). When combined with collective action, social learning can make transformative change, measured by a change in worldviews (beliefs about the world and reality) and understanding of power dynamics (Gupta 2014; Bamberg et al. 2015).

7.6.5 Land tenure

Land tenure, defined as 'the terms under which land and natural resources are held by individuals, households or social groups', is a key dimension in any discussion of land–climate interactions, including the prospects for both adaptation and land-based mitigation, and possible impacts on tenure and thus land security of both climate change and climate action (Quan and Dyer 2008) (*medium evidence*, *high agreement*).

Discussion of land tenure in the context of land–climate interactions in developing countries needs to consider the prevalence of informal, customary and modified customary systems of land tenure: estimates range widely, but perhaps as much as 65% of the world's total land area is managed under some form of these local, customary or communal tenure systems, and only a small fraction of this (around 15%) is formally recognised by governments (Rights and Resources Initiative 2015a). These customary land rights can extend across many categories of land, but are difficult to assess properly due to poor reporting, lack of legal recognition, and lack of access to reporting systems by indigenous and rural peoples (Rights and Resources Initiative 2018a). Around 521 million ha of forest land is estimated to be legally owned, recognised, or designated for use by indigenous and local communities as of 2017 (Rights and Resources Initiative 2018b), predominantly in Latin America, followed by Asia. However, in India approximately 40 million ha of forest land is managed under customary rights not recognised by the government (Rights and Resources Initiative 2015b). In 2005 only 1% of land in Africa was legally registered (Easterly 2008a).

Much of the world's carbon is stored in the biomass and soil on the territories of customary landowners, including indigenous peoples (Walker et al. 2014; Garnett et al. 2018), making securing of these land tenure regimes vital in land and climate protection. These lands are estimated to hold at least 293 GtC of carbon, of which around one-third (72 GtC) is located in areas where indigenous peoples and local communities lack formal recognition of their tenure rights (Frechette et al. 2018).

Understanding the interactions between land tenure and climate change has to be based on underlying understanding of land tenure and land policy and how they relate to sustainable development, especially in low- and middle-income countries: such understandings have changed considerably over the last three decades, and now show that informal or customary systems can provide secure tenure (Toulmin and Quan 2000). For smallholder systems, Bruce and Migot-Adholla (1994) (among other authors) established that African customary tenure can provide the necessary security for long-term investments in farm fertility such as tree-planting. For pastoral systems, Behnke (1994), Lane and Moorehead (1995) and other authors showed the rationality of communal tenure in situations of environmental variability and herd mobility. However, where customary systems are unrecognised or weakened by governments, or the rights from them are undocumented or unenforced, tenure insecurity may result (Lane 1998; Toulmin and Quan 2000). There is strong empirical evidence of the links between secure communal tenure and lower deforestation rates, particularly for intact forests (Nepstad et al. 2006; Persha et al. 2011; Vergara-Asenjo and Potvin 2014). Securing and recognising tenure for indigenous communities (such as through revisions to legal or policy frameworks) has been shown to be highly cost effective in reducing deforestation and improving land management in certain contexts, and is therefore also apt to help improve indigenous communities' ability to adapt to climate changes (Suzuki 2012; Balooni et al. 2008; Ceddia et al. 2015; Pacheco et al. 2012; Holland et al. 2017).

Rights to water for agriculture or livestock are linked to land tenure in complex ways still little understood and neglected by policymakers and planners (Cotula 2006a). Provision of water infrastructure tends to increase land values, but irrigation schemes often entail reallocation of land rights (Cotula 2006b) and new inequalities based on water availability such as the creation of a category of tailenders (farmers at the downstream end of distribution channels) in large-scale irrigation (Chambers 1988) and disruption of pastoral grazing patterns through use of riverine land (Behnke and Kerven 2013).

Understanding land tenure under climate change also has to take account of the growth in large-scale land acquisitions (LSLAs), also referred to as land-grabbing, in developing countries. These LSLAs are defined by acquisition of more than 200 ha per deal (Messerli et al. 2014a). Klaus Deininger (2011) links the growth in demand for land to the 2007–2008 food price spike, and demonstrates that high levels of demand for land at the country level are statistically associated with weak recognition of land rights. Land grabs, where LSLAs occur despite local use of lands, are often driven by direct collaboration of politicians, government officials and land agencies (Koechlin et al. 2016), involving corruption of governmental land agencies, failures to register community land claims and illegal lands uses, and lack of the rule of law and enforcement in resource extraction frontiers (Borras Jr et al. 2011). Though data is poor, overall, small- and medium-scale domestic investment has in fact been more important than foreign investment (Deininger 2011; Cotula et al. 2014). There are variations in estimates of the scale of LSLAs: Nolte et al. (2016) concluded that deals totalled 42.2 million ha worldwide. Cotula et al. (2014) using cross-checked data for completed lease agreements in Ethiopia, Ghana and Tanzania conclude that they cover 1.9%, 1.9% and 1.1% respectively of each country's total land suitable for agriculture. The literature expresses different views on whether these acquisitions concern marginal lands or lands already in use, thereby displacing existing users (Messerli et al. 2014b). Land-grabbing is associated with, and may be motivated by, the acquisition of rights to water, and erosion of those rights for other users such as those downstream (Mehta et al. 2012). Quantification of the acquisition of water rights resulting from LSLAs raises major issues of definition, data availability, and measurement. One estimate of the total acquisition of gross irrigation water associated with land-grabbing across the 24 countries most affected is 280 billion m^3 (Rulli et al. 2013).

While some authors see LSLAs as investments that can contribute to more efficient food production at larger scales (World Bank 2011; Deininger and Byerlee 2012), others have warned that local food security may be threatened by them (Daniel 2011; Golay and Biglino 2013; Lavers 2012). Reports suggest that recent land-grabbing has affected 12 million people globally in terms of declines in welfare (Adnan 2013; Davis et al. 2014). De Schutter (2011) argues that large-scale land acquisitions will: a) result in types of farming less liable to reduce poverty than smallholder systems, b) increase local vulnerability to food price shocks by favouring export agriculture and c) accelerate the development of a market for land, with detrimental impacts on smallholders and those depending on common property resources. Land-grabbing can threaten not only agricultural lands of farmers, but also protected ecosystems, like forests and wetlands (Hunsberger et al. 2017; Carter et al. 2017; Ehara et al. 2018).

The primary mechanisms for combating LSLAs have included restrictions on the size of land sales (Fairbairn 2015), pressure on agribusiness companies to agree to Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security, known as VGGT, or similar principles (Collins 2014; Goetz 2013), attempts to repeal biofuels standards (Palmer 2014), strengthening of existing land law and land registration systems (Bebbington et al. 2018), use of community monitoring systems (Sheil et al. 2015), and direct protests against land acquisitions (Hall et al. 2015; Fameree 2016).

Table 7.7 sets out, in highly summarised form, some key findings on the multi-directional inter-relations between land tenure and climate change, with particular reference to developing countries. The rows represent different categories of landscape or resource systems. For each system the second column summarises current understandings on land tenure and sustainable development, in many cases predating concerns over climate change. The third column summarises the most important implications of land tenure systems, policy about land tenure, and the implementation of that policy, for vulnerability and adaptation to climate change, and the fourth column gives a similar summary for mitigation of climate change. The fifth column summarises key findings on how climate change and climate action (both adaptation and mitigation) will impact land tenure, and the final column, findings on implications of climate change for evolving land policy.

Table 7.7 | Major findings on the interactions between land tenure and climate change.

Landscape or natural resource system	State of understanding of land tenure, land policy and sustainable development	Implications of land tenure for vulnerability and adaptation to climate change	Implications of land tenure for mitigation of climate change	Impacts of climate change and climate action on land tenure	Implications of climate change and climate action for land policy
Smallholder cropland	In South Asia and Latin America, the poor suffer from limited access, including insecure tenancies, though this has been partially alleviated by land reform.[1] In Africa informal/customary systems may provide considerable land tenure security and enable long-term investment in land management, but are increasingly weakened by demographic pressures on available land resources increase. However, creation of freehold rights through conventional land titling is not a necessary condition for tenure security and may be cost-ineffective or counterproductive.[2,3,4,5] Alternative approaches utilising low-cost technologies and participatory methods are available.[6] Secure and defendable land tenure, including modified customary tenure, has been positively correlated with food production increases.[7,8,9]	Insecure land rights are one factor deterring adaptation and accentuating vulnerability.[10,11] Specific dimensions of inequity in customary systems may act as constraints on adaptation in different contexts.[12] Large-scale land acquisitions (LSLAs) may be associated with monoculture and other unsustainable land-use practices, have negative consequences for soil degradation[13] and disincentivise more sustainable forms of agriculture.[14]	Secure land rights, including through customary systems, can incentivise farmers to adopt long-term climate-smart practices,[15] e.g., planting trees in mixed cropland/forest systems.[16]	Increased frequency and intensity of extreme weather can lead to displacement and effective loss of land rights.[17] REDD+ (reducing emissions from deforestation and forest degradation) programmes tend slightly to increase land tenure insecurity on agricultural forest frontier lands – but not in forests.[18]	Landscape governance and resource tenure reforms at farm and community levels can facilitate and incentivise planning for landscape management and enable the integration of adaptation and mitigation strategies.[11]
Rangelands	Communal management of rangelands in pastoral systems is a rational and internally sustainable response to climate variability and the need for mobility. Policies favouring individual or small group land-tenure may have negative impacts on both ecosystems and livelihoods.[19,20,21]	Many pastoralists in lands at risk from desertification do not have secure land tenure, and erosion of traditional communal rangeland tenure has been identified as a determinant of increasing vulnerability to drought and climate change and as a driver of dryland degradation.[22,23,24,25,26]	Where pastoralists' traditional land use does not have legal recognition, or where pastoralists are unable to exclude others from land use, this presents significant challenges for carbon sequestration initiatives.[27,28]	Increasing conflict on rangelands is a possible result of climate change and environmental pressures, but depends on local institutions.[29] Where land-use rights for pastoralists are absent or unenforced, demonstrated potential for carbon sequestration may assist advocacy.[28]	Carbon sequestration initiatives on rangelands may require clarification and maintenance of land rights.[27,28]

Landscape or natural resource system	State of understanding of land tenure, land policy and sustainable development	Implications of land tenure for vulnerability and adaptation to climate change	Implications of land tenure for mitigation of climate change	Impacts of climate change and climate action on land tenure	Implications of climate change and climate action for land policy
Forests	Poor management of state and open-access forests has been combated in recent years by a move towards forest decentralisation and community co-management.[30,31,32,33,34,35] Land tenure systems have complex interactions with deforestation processes. Land tenure security is generally associated with less deforestation, regardless of whether the tenure form is private, customary or communal.[33,36,37,38] Historical injustices towards forest dwellers can be ameliorated with appropriate policy, e.g., 2006 Forest Rights Act in India.[39]	Land tenure security can lead to improved adaptation outcomes[40,41,42,43] but land tenure policy for forests that focuses narrowly on cultivation has limited ability to reduce ecological vulnerability or enhance adaptation.[39] Secure rights to land and forest resources can facilitate efforts to stabilise shifting cultivation and promote more sustainable resource use if appropriate technical and market support are available.[44]	Land tenure insecurity has been identified as a key driver of deforestation and land degradation, leading to loss of sinks and creating sources of GHGs.[45,46,47,48,49] While land tenure systems interact with land-based mitigation actions in complex ways,[36] forest decentralisation and community co-management has shown considerable success in slowing forest loss and contributing to carbon mitigation.[30,31,32,33,34,35] Communal tenure systems may lower transaction costs for REDD+ schemes, though with risk of elite capture of payments.[16]	Findings on both direction of change in tenure security and extent to which this has been influenced by REDD+ are very diverse.[18] The implications of land-based mitigation – e.g., bioenergy with carbon capture and storage (BECCS) – on land tenure systems is currently understudied, but evidence from biofuels expansion shows negative impacts on local livelihoods and loss of forest sinks where LSLAs override local land tenure.[50,51]	Forest tenure policies under climate change need to accommodate and enable evolving and shifting boundaries linked to changing forest livelihoods.[10] REDD+ programmes need to be integrated with national-level forest tenure reform.[18]
Poor and informal urban settlements	Residents of poor and informal urban settlements enjoy varying degrees of tenure security from different forms of tenure. Security will be increased by building on de facto rights rather than through abrupt changes in tenure systems.[52]	Public land on the outskirts of urban areas can be used to adapt to increasing flood risks by protecting natural assets.[53] Secure land titles in hazardous locations may make occupants reluctant to move and raise the costs of compensation and resettlement.[17]	Urban land-use strategies such as tree planting, establishing public parks, can save energy usage by moderating urban temperature and protect human settlement from natural disaster such as flooding or heatwaves.[54]	Without proper planning, climate hazards can undermine efforts to recognise and strengthen informal tenure rights without proper planning.[55,56]	Climate risks increase the requirements for land-use planning and settlement that increases tenure security, with direct involvement of residents, improved use of public land, and innovative collaboration with private and traditional land owners.[56,57]
Riverscapes and riparian fringes	Well-defined but spatially flexible community tenure can support regulated and sustainable artisanal capture fisheries and biodiversity.[58,59,60,61,62,63,64]	Unequal land rights and absence of land management arrangements in floodplains increases vulnerability and constrains adaptation.[65] Marginalised or landless fisherfolk will be empowered by tenurial rights and associated identity to respond more effectively to ecological changes in riverscapes, including riparian zones.[66,67,68,69]	Mitigation measures such as protection of riparian forests and grasslands can potentially play a major role, provided rights to land and trees are sufficiently clear.[70,71]		Secured but spatially flexible tenure will enable climate change mitigation in riverscapes to be synergised with local livelihoods and ecological security.[67,72]

Sources: 1) Binswanger et al. 1995; 2) Schlager and Ostrom 1992; 3) Toulmin and Quan 2000; 4) Bruce and Migot-Adholla 1994; 5) Easterly 2008; 6) McCall and Dunn 2012; 7) Maxwell and Wiebe 1999; 8) Holden and Ghebru 2016; 9) Corsi et al. 2017; 10) Quan et al. 2017; 11) Harvey et al. 2014; 12) Antwi-Agyei et al. 2015; 13) Balehegn 2015; 14) Friis and Nielsen, 2016; 15) Scherr et al. 2012; 16) Barbier and Tesfaw 2012; 17) Mitchell 2010; 18) Sunderlin et al. 2018; 19) Behnke 1994; 20) Lane and Moorehead 1995; 21) Davies et al. 2015; 22) Morton 2007; 23) López-i-Gelats et al. 2016; 24) Oba 1994; 25) Fraser et al. 2011; 26) Dougill et al. 2011; 27) Roncoli et al. 2007; 28) Tennigkeit and Wilkes 2008; 29) Adano et al. 2012; 30) Agrawal et al. 2008; 31) Chhatre and Agrawal, 2009; 32) Gabay and Alam, 2017; 33) Holland et al. 2017; 34) Larson and Pulhin, 2012; 35) Pagdee et al. 2006; 36) Robinson et al. 2014; 37) Blackman et al. 2017; 38) Nelson et al. 2001; 39) Ramnath 2008; 40) Suzuki 2012; 41) Balooni et al. 2008; 42) Ceddia et al. 2015; 43) Pacheco et al. 2012; 44) Garnett et al. 2013; 45) Clover and Eriksen, 2009; 46) Damnyag et al. 2012; 47) Finley-Brook 2007; 48) Robinson et al. 2014; 49) Stickler et al. 2017; 50) Romijn 2011; 51) Aha and Ayitey 2017; 52) Payne 2001; 53) Barbedo et al. 2015; 54) Zhao et al. 2018; 55) Satterthwaite et al. 2018; 56) Mitchell et al. 2015; 57) Satterthwaite 2007; 58) Thomas 1996; 59) Welcomme et al. 2010; 60) Silvano and Valbo-Jørgensen 2008; 61) Biermann et al. 2012; 62) Abbott et al. 2007; 63) Béné et al. 2011; 64) McGrath et al. 1993; 65) Barkat et al. 2001; 66) FAO 2015; 67) Hall et al. 2013; 68) Berkes 2001; 69) ISO 2017; 70) Rocheleau and Edmunds 1997; 71) Baird and Dearden 2003; 72) Béné et al. 2010.

In drylands, weak land tenure security, either for households disadvantaged within a customary tenure system or more widely as such a system is eroded, can be associated with increased vulnerability and decreased adaptive capacity (*limited evidence*, *high agreement*). There is *medium evidence* and *medium agreement* that land titling and recognition programmes, particularly those that authorise and respect indigenous and communal tenure, can lead to improved management of forests, including for carbon storage (Suzuki 2012; Balooni et al. 2008; Ceddia et al. 2015; Pacheco et al. 2012), primarily by providing legally secure mechanisms for exclusion of others (Nelson et al. 2001; Blackman et al. 2017). However, these titling programmes are highly context-dependent and there is also evidence that titling can exclude community and common management, leading to more confusion over land rights, not less, where poorly implemented (Broegaard et al. 2017). For all the systems, an important finding is that land policies can provide both security and flexibility in the face of climate change, but through a diversity of forms and approaches (recognition of customary tenure, community mapping, redistribution, decentralisation, co-management, regulation of rental markets, strengthening the negotiating position of the poor) rather than sole focus on freehold title (*medium evidence*, *high agreement*) (Quan and Dyer, 2008; Deininger and Feder 2009; St. Martin 2009). Land policy can be climate-proofed and integrated with national policies such as National Adaptation Programme of Action NAPAs (Quan and Dyer 2008). Land administration systems have a vital role in providing land tenure security, especially for the poor, especially when linked to an expanded range of information relevant to mitigation and adaptation (Quan and Dyer 2008; van der Molen and Mitchell 2016). Challenges to such a role include outdated and overlapping national land and forest tenure laws, which often fail to recognise community property rights and corruption in land administration (Monterrosso et al. 2017), as well as lack of political will and the costs of improving land administration programmes (Deininger and Feder 2009).

7.6.6 Institutional dimensions of adaptive governance

Institutional systems that demonstrate the institutional dimensions, or indicators (Table 7.8) enhance the adaptive capacity of the socio-ecological system to a greater degree than institutional systems that do not demonstrate these dimensions (*high confidence*) (Gupta et al. 2010; Mollenkamp and Kasten 2009). Governance processes and policy instruments supporting these characteristics are context specific (*medium evidence*, *high agreement*) (Biermann 2007; Gunderson and Holling 2001; Hurlbert and Gupta 2017; Bastos Lima et al. 2017a; Gupta et al. 2013a; Mollenkamp and Kasten 2009; Nelson et al. 2010; Olsson et al. 2006; Ostrom 2011; Pahl-Wostl 2009; Verweij et al. 2006; Weick and Sutcliffe 2001).

Consideration of these indicators is important when implementing climate change mitigation instruments. For example, a 'variety,' redundancy, or duplication of climate mitigation policy instruments is an important consideration for meeting Paris Agreement commitments. Given that 58% of EU emissions are outside of the EU Emissions Trading System, implementation of a 'redundant' carbon tax may add co-benefits (Baranzini et al. 2017). Further, a carbon tax phased in over time through a schedule of increases allows for 'learning.' The tax revenues could be earmarked to finance additional climate change mitigation and/or redistributed to achieve the indicator of 'fair governance – equity'. It is recommended that carbon pricing measures be implemented using information-sharing and communication devices to enable public acceptance, openness, provide measurement and accountability (Baranzini et al. 2017; Siegmeier et al. 2018).

The impact of flood on a socio-ecological system is reduced with the governance indicator of both leadership and resources (Emerson and Gerlak 2014). 'Leadership' pertains to a broad set of stakeholders that facilitate adaptation (and might include scientists and leaders in NGOs) and those that respond to flood in an open, inclusive, and fair manner identifying the most pressing issues and actions needed. Resources are required to support this leadership and includes upfront financial investment in human capital, technology, and infrastructure (Emerson and Gerlak 2014).

Policy instruments advancing the indicator of 'participation' in community forest management include favourable loans, tax measures, and financial support to catalyse entrepreneurial leadership, and build in rewards for supportive and innovative elites to reduce elite capture and ensure more inclusive participation (Duguma et al. 2018) (Section 7.6.4).

Table 7.8 | Institutional dimensions or indicators of adaptive governance. This table represents a summation of characteristics, evaluative criteria, elements, indicators or institutional design principles that advance adaptive governance.

Indicators/Institutional dimensions	Description	References
Variety	Room for a variety of problem frames reflecting different opinions and problem definitions	Biermann 2007 Gunderson and Holling 2001 Hurlbert and Gupta 2017 Bastos Lima et al. 2017a Gupta, J., van der Grijp, N., Kuik 2013 Mollenkamp and Kasten 2009 Nelson et al. 2010 Olsson et al. 2006 Ostrom 2011 Pahl-Wostl 2009 Verweij et al. 2006 Weick and Sutcliffe 2001
	Participation. Involving different actors at different levels, sectors, and dimensions	
	Availability of a wide range or diversity of policy options to address a particular problem	
	Redundancy or duplication of measures, back-up systems	
Learning	Trust	
	Single loop learning or ability to improve routines based on past experience	
	Double loop learning or changed underlying assumptions of institutional patterns	
	Discussion of doubts (openness to uncertainties, monitoring and evaluation of policy experiences)	
	Institutional memory (monitoring and evaluation of policy experiences over time)	
Room for autonomous change	Continuous access to information (data institutional memory and early warning systems)	
	Acting according to plan (especially in relation to disasters)	
	Capacity to improvise (in relation to self-organisation and fostering social capital)	
Leadership	Visionary (long-term and reformist)	
	Entrepreneurial; leads by example	
	Collaborative	
Resources	Authority resources or legitimate forms of power	
	Human resources of expertise, knowledge and labour	
	Financial resources	
Fair governance	Legitimacy or public support	
	Equity in relation to institutional fair rules	
	Responsiveness to society	
	Accountability in relation to procedures	

7.6.7 Inclusive governance for sustainable development

Many sustainable development efforts fail because of lack of attention to societal issues, including inequality, discrimination, social exclusion and marginalisation (see Cross-Chapter Box 11 in this chapter) (Arts 2017a). However, the human-rights-based approach of the 2030 Agenda and Sustainable Development Goals commits to leaving no one behind (Arts 2017b). Inclusive governance focuses attention in issues of equity and the human-rights-based approach for development as it includes social, ecological and relational components used for assessing access to, as well as the allocations of rights, responsibilities and risks with respect to social and ecological resources (*medium agreement*) (Gupta and Pouw 2017).

Governance processes that are inclusive of all people in decision-making and management of land, are better able to make decisions addressing trade-offs of sustainable development (Gupta et al. 2015) and achieve SDGs focusing on social and ecological inclusiveness (Gupta and Vegelin 2016). Citizen engagement is important in enhancing natural resource service delivery by citizen inclusion in management and governance decisions (Section 7.5.5). In governing natural resources, focus is now not only on rights of citizens in relation to natural resources, but also on citizen obligations, responsibilities (Karar and Jacobs-Mata 2016; Chaney and Fevre 2001), feedback and learning processes (Tàbara et al. 2010). In this respect, citizen engagement is also an imperative, particularly for analysing and addressing aggregated informal coping strategies of local residents in developing countries, which are important drivers of natural resource depletions (but often overlooked in conventional policy development processes in natural resource management) (Ehara et al. 2018).

Inclusive adaptive governance makes important contributions to the management of risk. Inclusive governance concerning risk integrates people's knowledge and values by involving them in decision-making processes where they are able to contribute their respective knowledge and values to make effective, efficient, fair, and morally acceptable decisions (Renn and Schweizer 2009). Representation in decision-making would include major actors – government, economic sectors, the scientific community and representatives of civil society (Renn and Schweizer 2009). Inclusive governance focuses attention on the well-being and meaningful participation in decision-making of the poorest (in income), vulnerable (in terms of age, gender, and location), and the most marginalised, and is inclusive of all knowledges (Gupta et al. 2015).

7.7 Key uncertainties and knowledge gaps

Uncertainties in land, society and climate change processes are outlined in Section 7.2 and Chapter 1. This chapter has reviewed literature on risks arising from GHG fluxes, climate change, land degradation, desertification and food security, policy instruments responding to these risks, as well as decision-making and adaptive climate and land governance, in the face of uncertainty.

More research is required to understand the complex interconnections of land, climate, water, society, ES and food, including:

- new models that allow incorporation of considerations of justice, inequality and human agency in socio-environmental systems
- understanding how policy instruments and response options interact and augment or reduce risks in relation to acute shocks and slow-onset climate events
- understanding how response options, policy and instrument portfolios can reduce or augment the cascading impacts of land, climate and food security and ES interactions through different domains such as health, livelihoods and infrastructure, especially in relation to non-linear and tipping-point changes in natural and human systems
- consideration of trade-offs and synergies in climate, land, water, ES and food policies
- the impacts of increasing use of land due to climate mitigation measures such as BECCS, carbon-centric afforestation/REDD+ and their impacts on human conflict, livelihoods and displacement
- understanding how different land tenure systems, both formal and informal, and the land policies and administration systems that support them, can constrain or facilitate climate adaptation and mitigation, and on how forms of climate action can enhance or undermine land tenure security and land justice
- expanding understanding of barriers to implementation of land-based climate policies at all levels from the local to the global, including methods for monitoring and documenting corruption, misappropriation and elite capture in climate action
- identifying characteristics and attributes signalling impending socio-ecological tipping points and collapse
- understanding the full cost of climate change in the context of disagreement on accounting for climate change interactions and their impact on society, as well as issues of valuation, and attribution uncertainties across generations
- new models and Earth observation to understand the complex interactions described in this section
- the impacts, monitoring, effectiveness, and appropriate selection of certification and standards for sustainability (Section 7.4.6.3) (Stattman et al. 2018) and the effectiveness of its implementation through the landscape governance approach (Pacheco et al. 2016) (Section 7.6.3).

Actions to mitigate climate change are rarely evaluated in relation to impact on adaptation, SDGs, and trade-offs with food security. For instance, there is a gap in knowledge in the optimal carbon pricing or emission trading scheme together with monitoring, reporting and verification system for agricultural emissions that will advance GHG reductions, food security, and SLM. Better understanding is needed of the triggers and leveraging actions that build sustainable development and SLM, as well as the effective organisation of the science and society interaction jointly shaping policies in the future. What societal interaction in the future will form inclusive and equitable governance processes and achieve inclusive governance institutions, especially including land tenure?

As there is a significant gap in NDCs and achieving commitments to keep global warming well below 2°C (Section 7.4.4.1), governments might consider evaluating national, regional, and local gaps in knowledge surrounding response options, policy instruments portfolios, and SLM supporting the achievement of NDCs in the face of land and climate change.

Frequently Asked Questions

FAQ 7.1 | How can indigenous knowledge and local knowledge inform land-based mitigation and adaptation options?

Indigenous knowledge (IK) refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. Local knowledge (LK) refers to the understandings and skills developed by individuals and populations, specific to the place where they live. These forms of knowledge, jointly referred to as Indigenous and Local Knowledge or ILK, are often highly context specific and embedded in local institutions, providing biological and ecosystem knowledge with landscape information. For example, they can contribute to effective land management, predictions of natural disasters, and identification of longer-term climate changes, and ILK can be particularly useful where formal data collection on environmental conditions may be sparse. ILK is often dynamic, with knowledge holders often experimenting with mixes of local and scientific approaches. Water management, soil fertility practices, grazing systems, restoration and sustainable harvesting of forests, and ecosystem-based adaptation are many of the land management practices often informed by ILK. ILK can also be used as an entry point for climate adaptation by balancing past experiences with new ways to cope. To be effective, initiatives need to take into account the differences in power between the holders of different types of knowledge. For example, including indigenous and/or local people in programmes related to environmental conservation, formal education, land management planning and security tenure rights is key to facilitate climate change adaptation. Formal education is necessary to enhance adaptive capacity of ILK, since some researchers have suggested that these knowledge systems may become less relevant in certain areas where the rate of environmental change is rapid and the transmission of ILK between generations is becoming weaker.

FAQ 7.2 | What are the main barriers to and opportunities for land-based responses to climate change?

Land-based responses to climate change can be mitigation (e.g., renewable energy, vegetation or crops for biofuels, afforestation) or adaptation (e.g., change in cropping pattern, less water-intensive crops in response to moisture stress), or adaptation with mitigation co-benefits (e.g., dietary shifts, new uses for invasive tree species, siting solar farms on highly degraded land). Productive land is an increasingly scarce resource under climate change. In the absence of adequate deep mitigation in the less land-intensive energy sector, competition for land and water for mitigation and for other sectors such as food security, ecosystem services (ES) and biodiversity conservation could become a source of conflict and a barrier to land-based responses.

Barriers to land-based mitigation include opposition due to real and perceived trade-offs between land for mitigation and food security and ES. These can arise due to absence of or uncertain land and water rights. Significant upscaling of mitigation requires dedicated (normally land-based) sources in addition to use of wastes and residues. This requires high land-use intensity compared to other mitigation options that, in turn, place greater demands on governance. A key governance mechanism that has emerged in response to such concerns, especially during the past decade are standards and certification systems that include food security, and land and water rights, in addition to general criteria or indicators related to sustainable use of land and biomass, with an emphasis on participatory approaches. Other governance responses include linking land-based mitigation (e.g., forestry) to secure tenure and support for local livelihoods. A barrier to land-based mitigation is our choice of development pathway. Our window of opportunity – whether or not we face barriers or opportunities to land-based mitigation – depends on socio-economic decisions or pathways. If we have high population growth and resource intensive consumption (i.e., SSP3) we will have more barriers. High population and low land-use regulation results in less available space for land-based mitigation. But if we have the opposite trends (SSP1), we can have more opportunities.

Other barriers can arise when, in the short term, adaptation to a climate stress (e.g., increased dependence on groundwater during droughts) can become unsustainable in the longer term, and become a maladaptation. Policies and approaches that lead to land management that synergises multiple ES and reduce trade-offs could find greater acceptance and enjoy more success.

Opportunities to obtain benefits or synergies from land-based mitigation and adaptation arise from their relation to the land availability and the demand for such measures in rural areas that may otherwise lack incentives for investment in infrastructure, livelihoods and institutional capacity. After decades of urbanisation around the world, facilitated by significant investment in urban infrastructure and centralised energy and agricultural systems, rural areas have been somewhat neglected; this is even as farmers in these areas provide critical food and materials needed for urban areas. As land and biomass becomes more valuable, there will be benefits for farmers, forest owners and associated service providers as they diversify and feed into economic activities supporting bioenergy, value-added products, preservation of biodiversity and carbon sequestration (storage).

A related opportunity for benefits is the potentially positive transformation in rural and peri-urban landscapes that could be facilitated by investments that prioritise more effective management of ES and conservation of water, energy, nutrients and other resources that have been priced too low in relation to their environmental or ecological value. Multifunctional landscapes supplying food, feed, fibre and fuel to both local and urban communities, in combination with reduced waste and healthier diets, could restore the role of rural producers as stewards of resources rather than providing food at the lowest possible price. Some of these landscape transformations will function as both mitigation and adaptation responses by increasing resilience, even as they provide value-added bio-based products.

Governments can introduce a variety of regulations and economic instruments (taxes, incentives) to encourage citizens, communities and societies to adopt sustainable land management practices, with further benefits in addition to mitigation. Windows of opportunity for redesigning and implementing mitigation and adaptation can arise in the aftermath of a major disaster or extreme climate event. They can also arise when collective action and citizen science motivate voluntary shifts in lifestyles supported by supportive top-down policies.

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