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Framing and context

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Executive summary

Land, including its water bodies, provides the basis for human livelihoods and well-being through primary productivity, the supply of food, freshwater, and multiple other ecosystem services (*high confidence*). Neither our individual or societal identities, nor the world's economy would exist without the multiple resources, services and livelihood systems provided by land ecosystems and biodiversity. The annual value of the world's total terrestrial ecosystem services has been estimated at 75 trillion USD in 2011, approximately equivalent to the annual global Gross Domestic Product (based on USD2007 values) (*medium confidence*). Land and its biodiversity also represent essential, intangible benefits to humans, such as cognitive and spiritual enrichment, sense of belonging and aesthetic and recreational values. Valuing ecosystem services with monetary methods often overlooks these intangible services that shape societies, cultures and quality of life and the intrinsic value of biodiversity. The Earth's land area is finite. Using land resources sustainably is fundamental for human well-being (*high confidence*). {1.1.1}

The current geographic spread of the use of land, the large appropriation of multiple ecosystem services and the loss of biodiversity are unprecedented in human history (*high confidence*). By 2015, about three-quarters of the global ice-free land surface was affected by human use. Humans appropriate one-quarter to one-third of global terrestrial potential net primary production (*high confidence*). Croplands cover 12–14% of the global ice-free surface. Since 1961, the supply of global per capita food calories increased by about one-third, with the consumption of vegetable oils and meat more than doubling. At the same time, the use of inorganic nitrogen fertiliser increased by nearly ninefold, and the use of irrigation water roughly doubled (*high confidence*). Human use, at varying intensities, affects about 60–85% of forests and 70–90% of other natural ecosystems (e.g., savannahs, natural grasslands) (*high confidence*). Land use caused global biodiversity to decrease by around 11–14% (*medium confidence*). {1.1.2}

Warming over land has occurred at a faster rate than the global mean and this has had observable impacts on the land system (*high confidence*). The average temperature over land for the period 2006–2015 was 1.53°C higher than for the period 1850–1900, and 0.66°C larger than the equivalent global mean temperature change. These warmer temperatures (with changing precipitation patterns) have altered the start and end of growing seasons, contributed to regional crop yield reductions, reduced freshwater availability, and put biodiversity under further stress and increased tree mortality (*high confidence*). Increasing levels of atmospheric CO_2, have contributed to observed increases in plant growth as well as to increases in woody plant cover in grasslands and savannahs (*medium confidence*). {1.1.2}

Urgent action to stop and reverse the over-exploitation of land resources would buffer the negative impacts of multiple pressures, including climate change, on ecosystems and society (*high confidence*). Socio-economic drivers of land-use change such as technological development, population growth and increasing per capita demand for multiple ecosystem services are projected to continue into the future (*high confidence*). These and other drivers can amplify existing environmental and societal challenges, such as the conversion of natural ecosystems into managed land, rapid urbanisation, pollution from the intensification of land management and equitable access to land resources (*high confidence*). Climate change will add to these challenges through direct, negative impacts on ecosystems and the services they provide (*high confidence*). Acting immediately and simultaneously on these multiple drivers would enhance food, fibre and water security, alleviate desertification, and reverse land degradation, without compromising the non-material or regulating benefits from land (*high confidence*). {1.1.2, 1.2.1, 1.3.2–1.3.6, Cross-Chapter Box 1 in Chapter 1}

Rapid reductions in anthropogenic greenhouse gas (GHG) emissions that restrict warming to *"well-below"* 2°C would greatly reduce the negative impacts of climate change on land ecosystems (*high confidence*). In the absence of rapid emissions reductions, reliance on large-scale, land-based, climate change mitigation is projected to increase, which would aggravate existing pressures on land (*high confidence*). Climate change mitigation efforts that require large land areas (e.g., bioenergy and afforestation/reforestation) are projected to compete with existing uses of land (*high confidence*). The competition for land could increase food prices and lead to further intensification (e.g., fertiliser and water use) with implications for water and air pollution, and the further loss of biodiversity (*medium confidence*). Such consequences would jeopardise societies' capacity to achieve many Sustainable Development Goals (SDGs) that depend on land (*high confidence*). {1.3.1, Cross-Chapter Box 2 in Chapter 1}

Nonetheless, there are many land-related climate change mitigation options that do not increase the competition for land (*high confidence*). Many of these options have co-benefits for climate change adaptation (*medium confidence*). Land use contributes about one-quarter of global greenhouse gas emissions, notably CO_2 emissions from deforestation, CH_4 emissions from rice and ruminant livestock and N_2O emissions from fertiliser use (*high confidence*). Land ecosystems also take up large amounts of carbon (*high confidence*). Many land management options exist to both reduce the magnitude of emissions and enhance carbon uptake. These options enhance crop productivity, soil nutrient status, microclimate or biodiversity, and thus, support adaptation to climate change (*high confidence*). In addition, changes in consumer behaviour, such as reducing the over-consumption of food and energy would benefit the reduction of GHG emissions from land (*high confidence*). The barriers to the implementation of mitigation and adaptation options include skills deficit, financial and institutional barriers, absence of incentives, access to relevant technologies, consumer awareness and the limited spatial scale at which the success of these practices and methods have been demonstrated. {1.2.1, 1.3.2, 1.3.3, 1.3.4, 1.3.5, 1.3.6}

Sustainable food supply and food consumption, based on nutritionally balanced and diverse diets, would enhance food security under climate and socio-economic changes (*high confidence*). Improving food access, utilisation, quality and safety to enhance nutrition, and promoting globally equitable diets compatible with lower emissions have demonstrable positive impacts on land use and food security (*high confidence*). Food security is also negatively affected by food loss and waste (estimated as 25–30% of total food produced) (*medium confidence*). Barriers to improved food security include economic drivers (prices, availability and stability of supply) and traditional, social and cultural norms around food eating practices. Climate change is expected to increase variability in food production and prices globally (*high confidence*), but the trade in food commodities can buffer these effects. Trade can provide embodied flows of water, land and nutrients (*medium confidence*). Food trade can also have negative environmental impacts by displacing the effects of overconsumption (*medium confidence*). Future food systems and trade patterns will be shaped as much by policies as by economics (*medium confidence*). {1.2.1, 1.3.3}

A gender-inclusive approach offers opportunities to enhance the sustainable management of land (*medium confidence*). Women play a significant role in agriculture and rural economies globally. In many world regions, laws, cultural restrictions, patriarchy and social structures such as discriminatory customary laws and norms reduce women's capacity in supporting the sustainable use of land resources (*medium confidence*). Therefore, acknowledging women's land rights and bringing women's land management knowledge into land-related decision-making would support the alleviation of land degradation, and facilitate the take-up of integrated adaptation and mitigation measures (*medium confidence*). {1.4.1, 1.4.2}

Regional and country specific contexts affect the capacity to respond to climate change and its impacts, through adaptation and mitigation (*high confidence*). There is large variability in the availability and use of land resources between regions, countries and land management systems. In addition, differences in socio-economic conditions, such as wealth, degree of industrialisation, institutions and governance, affect the capacity to respond to climate change, food insecurity, land degradation and desertification. The capacity to respond is also strongly affected by local land ownership. Hence, climate change will affect regions and communities differently (*high confidence*). {1.3, 1.4}

Cross-scale, cross-sectoral and inclusive governance can enable coordinated policy that supports effective adaptation and mitigation (*high confidence*). There is a lack of coordination across governance levels, for example, local, national, transboundary and international, in addressing climate change and sustainable land management challenges. Policy design and formulation is often strongly sectoral, which poses further barriers when integrating international decisions into relevant (sub)national policies. A portfolio of policy instruments that are inclusive of the diversity of governance actors would enable responses to complex land and climate challenges (*high confidence*). Inclusive governance that considers women's and indigenous people's rights to access and use land enhances the equitable sharing of land resources, fosters food security and increases the existing knowledge about land use, which can increase opportunities for adaptation and mitigation (*medium confidence*). {1.3.5, 1.4.1, 1.4.2, 1.4.3}

Scenarios and models are important tools to explore the trade-offs and co-benefits of land management decisions under uncertain futures (*high confidence*). Participatory, co-creation processes with stakeholders can facilitate the use of scenarios in designing future sustainable development strategies (*medium confidence*). In addition to qualitative approaches, models are critical in quantifying scenarios, but uncertainties in models arise from, for example, differences in baseline datasets, land cover classes and modelling paradigms (*medium confidence*). Current scenario approaches are limited in quantifying time-dependent policy and management decisions that can lead from today to desirable futures or visions. Advances in scenario analysis and modelling are needed to better account for full environmental costs and non-monetary values as part of human decision-making processes. {1.2.2, Cross-Chapter Box 1 in Chapter 1}

1.1 Introduction and scope of the report

1.1.1 Objectives and scope of the assessment

Land, including its water bodies, provides the basis for our livelihoods through basic processes such as net primary production that fundamentally sustain the supply of food, bioenergy and freshwater, and the delivery of multiple other ecosystem services and biodiversity (Hoekstra and Wiedmann 2014; Mace et al. 2012; Newbold et al. 2015; Runting et al. 2017; Isbell et al. 2017) (Cross-Chapter Box 8 in Chapter 6). The annual value of the world's total terrestrial ecosystem services has been estimated to be about 75 trillion USD in 2011, approximately equivalent to the annual global Gross Domestic Product (based on USD2007 values) (Costanza et al. 2014; IMF 2018). Land also supports non-material ecosystem services such as cognitive and spiritual enrichment and aesthetic values (Hernández-Morcillo et al. 2013; Fish et al. 2016), intangible services that shape societies, cultures and human well-being. Exposure of people living in cities to (semi-)natural environments has been found to decrease mortality, cardiovascular disease and depression (Rook 2013; Terraube et al. 2017). Non-material and regulating ecosystem services have been found to decline globally and rapidly, often at the expense of increasing material services (Fischer et al. 2018; IPBES 2018a). Climate change will exacerbate diminishing land and freshwater resources, increase biodiversity loss, and will intensify societal vulnerabilities, especially in regions where economies are highly dependent on natural resources. Enhancing food security and reducing malnutrition, whilst also halting and reversing desertification and land degradation, are fundamental societal challenges that are increasingly aggravated by the need to both adapt to and mitigate climate change impacts without compromising the non-material benefits of land (Kongsager et al. 2016; FAO et al. 2018).

Annual emissions of GHGs and other climate forcers continue to increase unabatedly. *Confidence* is *very high* that the window of opportunity, the period when significant change can be made, for limiting climate change within tolerable boundaries is rapidly narrowing (Schaeffer et al. 2015; Bertram et al. 2015; Riahi et al. 2015; Millar et al. 2017; Rogelj et al. 2018a). The Paris Agreement formulates the goal of limiting global warming this century to well below 2°C above pre-industrial levels, for which rapid actions are required across the energy, transport, infrastructure and agricultural sectors, while factoring in the need for these sectors to accommodate a growing human population (Wynes and Nicholas 2017; Le Quere et al. 2018). Conversion of natural land, and land management, are significant net contributors to GHG emissions and climate change, but land ecosystems are also a GHG sink (Smith et al. 2014; Tubiello et al. 2015; Le Quere et al. 2018; Ciais et al. 2013a). It is not surprising, therefore, that land plays a prominent role in many of the Nationally Determined Contributions (NDCs) of the parties to the Paris Agreement (Rogelj et al. 2018a,b; Grassi et al. 2017; Forsell et al. 2016), and land-measures will be part of the NDC review by 2023.

A range of different climate change mitigation and adaptation options on land exist, which differ in terms of their environmental and societal implications (Meyfroidt 2018; Bonsch et al. 2016; Crist et al. 2017; Humpenoder et al. 2014; Harvey and Pilgrim 2011; Mouratiadou et al. 2016; Zhang et al. 2015; Sanz-Sanchez et al. 2017; Pereira et al. 2010; Griscom et al. 2017; Rogelj et al. 2018a) (Chapters 4–6). The Special Report on climate change, desertification, land degradation, sustainable land management, food security, and GHG fluxes in terrestrial ecosystems (SRCCL) synthesises the current state of scientific knowledge on the issues specified in the report's title (Figure 1.1 and Figure 1.2). This knowledge is assessed in the context of the Paris Agreement, but many of the SRCCL issues concern other international conventions such as the United Nations Convention on Biodiversity (UNCBD), the UN Convention to Combat Desertification (UNCCD), the UN Sendai Framework for Disaster Risk Reduction (UNISDR) and the UN Agenda 2030 and its Sustainable Development Goals (SDGs). The SRCCL is the first report in which land is the central focus since the IPCC Special Report on land use, land-use change and forestry (Watson et al. 2000) (Box 1.1). The main objectives of the SRCCL are to:

1. Assess the current state of the scientific knowledge on the impacts of socio-economic drivers and their interactions with climate change on land, including degradation, desertification and food security;
2. Evaluate the feasibility of different land-based response options to GHG mitigation, and assess the potential synergies and trade-offs with ecosystem services and sustainable development;
3. Examine adaptation options under a changing climate to tackle land degradation and desertification and to build resilient food systems, as well as evaluating the synergies and trade-offs between mitigation and adaptation;
4. Delineate the policy, governance and other enabling conditions to support climate mitigation, land ecosystem resilience and food security in the context of risks, uncertainties and remaining knowledge gaps.

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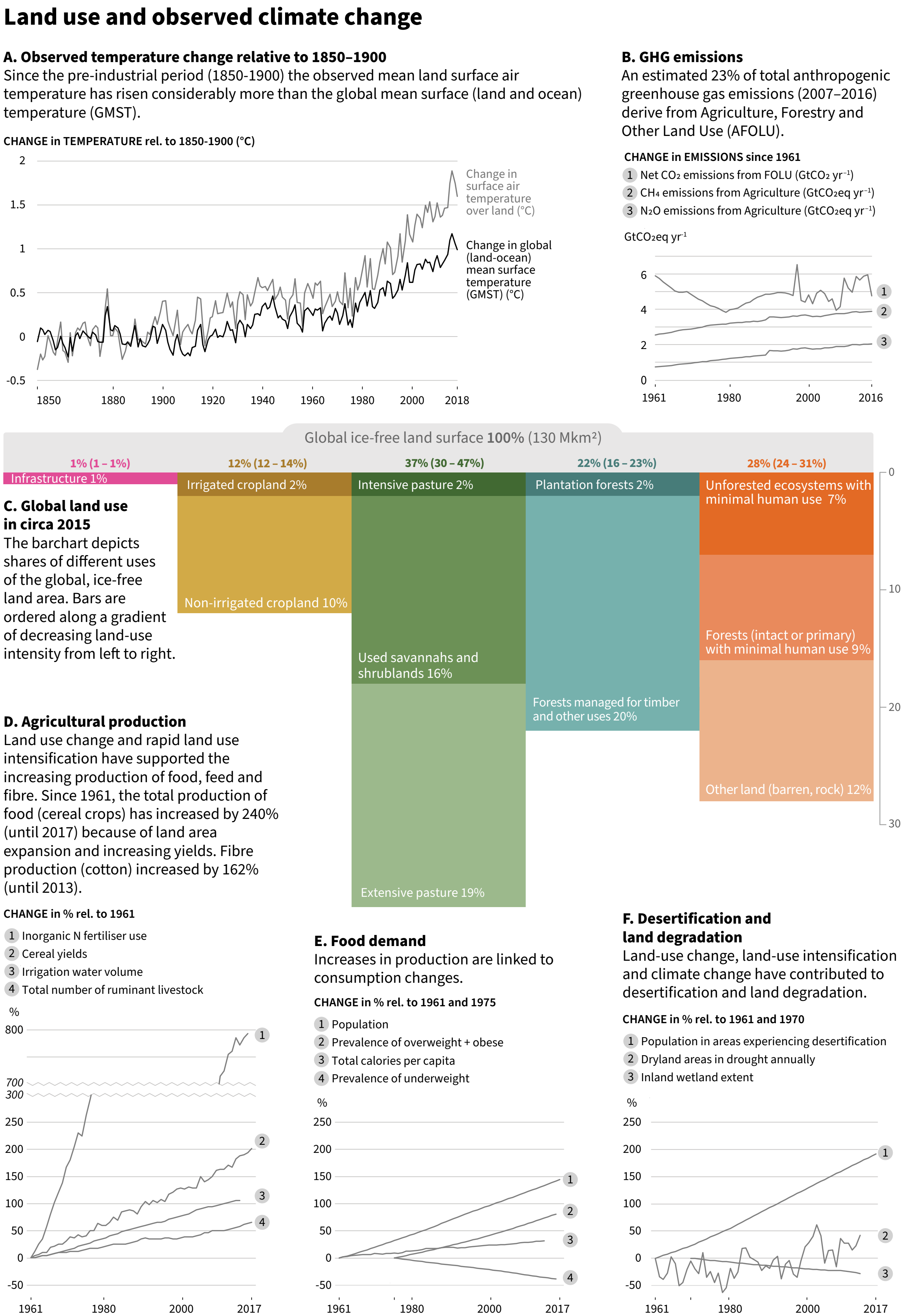

Figure 1.1 | A representation of the principal land challenges and land-climate system processes covered in this assessment report.

Figure 1.1 (continued): A. The warming curves are averages of four datasets (Section 2.1, Figure 2.2 and Table 2.1). **B.** N_2O and CH_4 from agriculture are from FAOSTAT; Net land-use change emissions of CO_2 from forestry and other land use (including emissions from peatland fires since 1997) are from the annual Global Carbon Budget, using the mean of two bookkeeping models. All values expressed in units of CO_2-eq are based on AR5 100-year Global Warming Potential values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28) (Table SPM.1 and Section 2.3). **C.** Depicts shares of different uses of the global, ice-free land area for approximately the year 2015, ordered along a gradient of decreasing land-use intensity from left to right. Each bar represents a broad land cover category; the numbers on top are the total percentage of the ice-free area covered, with uncertainty ranges in brackets. Intensive pasture is defined as having a livestock density greater than 100 animals/km^2. The area of 'forest managed for timber and other uses' was calculated as total forest area minus 'primary/intact' forest area. (Section 1.2, Table 1.1, Figure 1.3). **D.** Note that fertiliser use is shown on a split axis (source: International Fertiliser Industry Association, www.ifastat.org/databases). The large percentage change in fertiliser use reflects the low level of use in 1961 and relates to both increasing fertiliser input per area as well as the expansion of fertilised cropland and grassland to increase food production (1.1, Figure 1.3). **E.** Overweight population is defined as having a body mass index (BMI) >25 kg m^{-2} (source: Abarca-Gómez et al. 2017); underweight is defined as BMI <18.5 kg m^{-2}. (Population density, source*: United Nations, Department of Economic and Social Affairs 2017*) (Sections 5.1 and 5.2). **F.** Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980–2015) (Abatzoglou et al. 2018) to identify areas where the Aridity Index is below 0.65. Areas experiencing human caused desertification, after accounting for precipitation variability and CO_2 fertilisation, are identified in Le et al. 2016. Population data for these areas were extracted from the gridded historical population database HYDE3.2 (Goldewijk et al. 2017). Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index (Ziese et al. 2014). The area in drought was calculated for each month (Drought Index below –1), and the mean over the year was used to calculate the percentage of drylands in drought that year. The inland wetland extent (including peatlands) is based on aggregated data from more than 2000 time series that report changes in local wetland area over time (Dixon et al. 2016; Darrah et al. 2019) (Sections 3.1, 4.2 and 4.6).

Box 1.1 | Land in previous IPCC and other relevant reports

Previous IPCC reports have made reference to land and its role in the climate system. Threats to agriculture, forestry and other ecosystems, but also the role of land and forest management in climate change, have been documented since the IPCC Second Assessment Report, especially so in the Special Report on land use, land-use change and forestry (Watson et al. 2000). The IPCC Special Report on extreme events (SREX) discussed sustainable land management, including land-use planning, and ecosystem management and restoration among the potential low-regret measures that provide benefits under current climate and a range of future, climate change scenarios. Low-regret measures are defined in the report as those with the potential to offer benefits now and lay the foundation for tackling future, projected change. Compared to previous IPCC reports, the SRCCL offers a more integrated analysis of the land system as it embraces multiple direct and indirect drivers of natural resource management (related to food, water and energy securities), which have not previously been addressed to a similar depth (Field et al. 2014a; Edenhofer et al. 2014).

The recent IPCC Special Report on Global Warming of 1.5°C (SR15) targeted specifically the Paris Agreement, without exploring the possibility of future global warming trajectories above 2°C (IPCC 2018). Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services for people. In many scenarios proposed in this report, large-scale land use features as a mitigation measure. In the reports of the Food and Agriculture Organization (FAO), land degradation is discussed in relation to ecosystem goods and services, principally from a food security perspective (FAO and ITPS 2015). The UNCCD report (2014) discusses land degradation through the prism of desertification. It devotes due attention to how land management can contribute to reversing the negative impacts of desertification and land degradation. The IPBES assessments (2018a, b, c, d, e) focus on biodiversity drivers, including a focus on land degradation and desertification, with poverty as a limiting factor. The reports draw attention to a world in peril in which resource scarcity conspires with drivers of biophysical and social vulnerability to derail the attainment of sustainable development goals. As discussed in Chapter 4 of the SRCCL, different definitions of degradation have been applied in the IPBES degradation assessment (IPBES 2018b), which potentially can lead to different conclusions for restoration and ecosystem management.

The SRCCL complements and adds to previous assessments, whilst keeping the IPCC-specific 'climate perspective'. It includes a focussed assessment of risks arising from maladaptation and land-based mitigation (i.e. not only restricted to direct risks from climate change impacts) and the co-benefits and trade-offs with sustainable development objectives. As the SRCCL cuts across different policy sectors it provides the opportunity to address a number of challenges in an integrative way at the same time, and it progresses beyond other IPCC reports in having a much more comprehensive perspective on land.

The SRCCL identifies and assesses land-related challenges and response options in an integrative way, aiming to be policy relevant across sectors. Chapter 1 provides a synopsis of the main issues addressed in this report, which are explored in more detail in Chapters 2–7. Chapter 1 also introduces important concepts and definitions and highlights discrepancies with previous reports that arise from different objectives (a full set of definitions is provided in the Glossary). Chapter 2 focuses on the natural system dynamics, assessing recent progress towards understanding the impacts of climate change on land, and the feedbacks arising from altered biogeochemical and biophysical exchange fluxes (Figure 1.2).

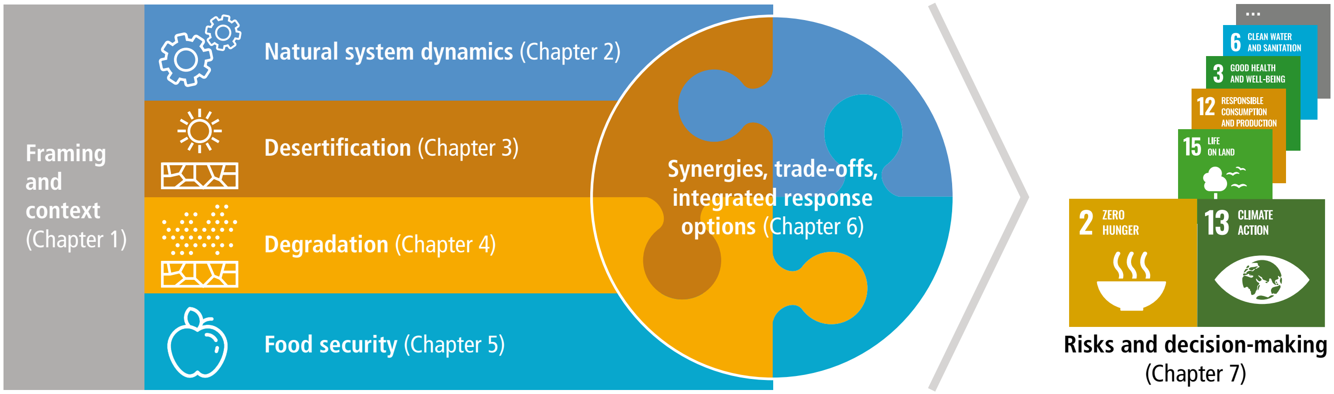

Figure 1.2 | Overview over the SRCCL.

Chapter 3 examines how the world's dryland populations are uniquely vulnerable to desertification and climate change, but also have significant knowledge in adapting to climate variability and addressing desertification. Chapter 4 assesses the urgency of tackling land degradation across all land ecosystems. Despite accelerating trends of land degradation, reversing these trends is attainable through restoration efforts and proper implementation of sustainable land management (SLM), which is expected to improve resilience to climate change, mitigate climate change, and ensure food security for generations to come. Food security is the focus of Chapter 5, with an assessment of the risks and opportunities that climate change presents to food systems, considering how mitigation and adaptation can contribute to both human and planetary health.

Chapter 6 focuses on the response options within the land system that deal with trade-offs and increase benefits in an integrated way in support of the SDGs. Chapter 7 highlights these aspects further, by assessing the opportunities, decision-making and policy responses to risks in the climate-land-human system.

1.1.2 Status and dynamics of the (global) land system

1.1.2.1 Land ecosystems and climate change

Land ecosystems play a key role in the climate system, due to their large carbon pools and carbon exchange fluxes with the atmosphere (Ciais et al. 2013b). Land use, the total of arrangements, activities and inputs applied to a parcel of land (such as agriculture, grazing, timber extraction, conservation or city dwelling; see Glossary), and land management (sum of land-use practices that take place within broader land-use categories; see Glossary) considerably alter terrestrial ecosystems and play a key role in the global climate system. An estimated one-quarter of total anthropogenic GHG emissions arise mainly from deforestation, ruminant livestock and fertiliser application (Smith et al. 2014; Tubiello et al. 2015; Le Quere et al. 2018; Ciais et al. 2013a), and especially methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture have been rapidly increasing over the last decades (Hoesly et al. 2018; Tian et al. 2019) (Figure 1.1 and Sections 2.3.2–2.3.3).

Globally, land also serves as a large CO_2 sink, which was estimated for the period 2008–2017 to be nearly 30% of total anthropogenic emissions (Le Quere et al. 2015; Canadell and Schulze 2014; Ciais et al. 2013a; Zhu et al. 2016) (Section 2.3.1). This sink has been attributed to increasing atmospheric CO_2 concentration, a prolonged growing season in cool environments, or forest regrowth (Le Quéré et al. 2013; Pugh et al. 2019; Le Quéré et al. 2018; Ciais et al. 2013a; Zhu et al. 2016). Whether or not this sink will persist into the future is one of the largest uncertainties in carbon cycle and climate modelling (Ciais et al. 2013a; Bloom et al. 2016; Friend et al. 2014; Le Quere et al. 2018). In addition, changes in vegetation cover caused by land use (such as conversion of forest to cropland or grassland, and vice versa) can result in regional cooling or warming through altered energy and momentum transfer between ecosystems and the atmosphere. Regional impacts can be substantial, but whether the effect leads to warming or cooling depends on the local context (Lee et al. 2011; Zhang et al. 2014; Alkama and Cescatti 2016) (Section 2.6). Due to the current magnitude of GHG emissions and CO_2 carbon dioxide removal in land ecosystems, there is *high confidence* that GHG reduction measures in agriculture, livestock management and forestry would have substantial climate change mitigation potential, with co-benefits for biodiversity and ecosystem services (Smith and Gregory 2013; Smith et al. 2014; Griscom et al. 2017) (Sections 2.6 and 6.3).

The mean temperature over land for the period 2006–2015 was 1.53°C higher than for the period 1850–1900, and 0.66°C larger than the equivalent global mean temperature change (Section 2.2). Climate change affects land ecosystems in various ways (Section 7.2). Growing seasons and natural biome boundaries shift in response to warming or changes in precipitation (Gonzalez et al. 2010; Wärlind et al. 2014; Davies-Barnard et al. 2015; Nakamura et al. 2017). Atmospheric CO_2 increases have been attributed to underlie, at least partially, observed woody plant cover increase in grasslands and savannahs (Donohue et al. 2013). Climate change-induced shifts in habitats, together with warmer temperatures, cause pressure on plants and animals (Pimm et al. 2014; Urban et al. 2016). National cereal crop losses of nearly 10% have been estimated for the period 1964–2007 as a consequence of heat and drought weather extremes (Deryng et al. 2014; Lesk et al. 2016). Climate change is expected to reduce yields in areas that are already under heat and water stress (Schlenker and Lobell 2010; Lobell et al. 2011, 2012; Challinor et al. 2014) (Section 5.2.2). At the same time, warmer temperatures can increase productivity in cooler regions (Moore and Lobell 2015) and might open opportunities for crop area expansion, but any overall benefits might be counterbalanced by reduced suitability in warmer regions (Pugh et al. 2016; Di Paola et al. 2018). Increasing atmospheric CO_2 is expected to increase productivity and water use efficiency in crops and in forests (Muller et al. 2015; Nakamura et al. 2017; Kimball 2016). The increasing number of extreme weather events linked to climate change is also expected to result in forest losses; heat waves and droughts foster wildfires (Seidl et al. 2017; Fasullo et al. 2018) (Cross-Chapter Box 3 in Chapter 2). Episodes of observed enhanced tree mortality across many world regions have been attributed to heat and drought stress (Allen et al. 2010; Anderegg et al. 2012), whilst weather extremes also impact local infrastructure and hence transportation and trade in land-related goods (Schweikert et al. 2014; Chappin and van der Lei 2014). Thus, adaptation is a key challenge to reduce adverse impacts on land systems (Section 1.3.6).

1.1.2.2 Current patterns of land use and land cover

Around three-quarters of the global ice-free land, and most of the highly productive land area, are by now under some form of land use (Erb et al. 2016a; Luyssaert et al. 2014; Venter et al. 2016) (Table 1.1). One-third of used land is associated with changed land cover. Grazing land is the single largest land-use category, followed by used forestland and cropland. The total land area used to raise livestock is notable: it includes all grazing land and an estimated additional

Table 1.1 | Extent of global land use and management around the year 2015.

	Best guess	Range		Range	Type	Reference
	[million km^2]		[% of total]			
Total	130.4		100%			
USED LAND	92.6	90.0–99.3	71%	69–76%		
Infrastructure (settlements, mining, etc.)	**1.4**	**1.2–1.9**	**1%**		**LCC**	1,2,3,4,5,6
Cropland	**15.9**	**15.9–18.8**	**12%**	**12–14%**		1,7
Irrigated cropland	3.1		2%		LCC	8
Non-irrigated cropland	12.8	12.8–15.7	10%		LCC	8
Grazing land	**48.0**	**38.8–61.9**	**37%**	**30–47%**		
Permanent pastures	**27.1**	**22.8–32.8**	**21%**	**17–25%**		5,7,8
Intensive permanent pastures[a]	2.6		2%		LCC	8,9
Extensive permanent pastures, on potential forest sites[b]	8.7		7%		LCC	9
Extensive permanent pastures, on natural grasslands[b]	15.8	11.5–21.6	12%	9–16%	LM	
Non-forested, used land, multiple uses[c]	**20.1**	**6.1–39.1**	**16%**	**5–30%**	**LM**	
Used forests[d]	**28.1**	**20.3–30.5**	**22%**	**16–23%**		10,11,12
Planted forests	2.9		2%		LCC	12
Managed for timber and other uses	25.2	17.4–27.6	20%	13–21%	LM	12
UNUSED LAND	37.0	31.1–40.4	28%	24–31%		5,11,13
Unused, unforested ecosystems, including grasslands and wetlands	9.4	5.9–10.4	7%	5–8%		1,13
Unused forests (intact or primary forests)	12.0	11.7–12.0	9%			11,12
Other land (barren wilderness, rocks, etc.)	15.6	13.5–18.0	12%	10–14%		4,5,13,14
Land-cover conversions (sum of LCC)	31.5	31.3–34.9	24%	24–27%		
Land-use occurring within natural land-cover types (sum of LM)	61.1	55.1–68.0	47%	42–52%		

[a] >100 animals/km^2.

[b] <100 animals/km^2, residual category within permanent pastures.

[c] Calculated as residual category. Contains land not classified as forests or cropland, such as savannah and tundra used as rangelands, with extensive uses like seasonal, rough grazing, hunting, fuelwood collection outside forests, wild products harvesting, etc.

[d] Used forest calculated as total forest minus unused forests.

Note: This table is based on data and approaches described in Lambin and Meyfroidt (2011, 2014); Luyssaert et al. (2014); Erb et al. (2016a), and references below. The target year for data is 2015, but proportions of some subcategories are from 2000 (the year with the most reconciled datasets available) and their relative extent was applied to some broad land-use categories for 2015. Sources: Settlements (1) Luyssaert et al. 2014; (2) Lambin and Meyfroidt 2014; (3) Global Human Settlements dataset, https://ghsl.jrc.ec.europa.eu/. Total infrastrucure including transportation (4) Erb et al. 2007; (5) Stadler et al. 2018; mining (6) Cherlet et al. 2018; (7) FAOSTAT 2018; (8) proportions from Erb et al. 2016a; (9) Ramankutty et al. 2008 extrapolated from 2000–2010 trend for permanent pastures from (7); (9) Erb et al. 2017; (10) Schepaschenko et al. 2015; (11) Potapov et al. 2017; (12) FAO 2015a; (13) Venter et al. 2016; (14) Ellis et al. 2010.

one-fifth of cropland for feed production (Foley et al. 2011). Globally, 60–85% of the total forested area is used, at different levels of intensity, but information on management practices globally is scarce (Erb et al. 2016a). Large areas of unused (primary) forests remain only in the tropics and northern boreal zones (Luyssaert et al. 2014; Birdsey and Pan 2015; Morales-Hidalgo et al. 2015; Potapov et al. 2017; Erb et al. 2017), while 73–89% of other, non-forested natural ecosystems (natural grasslands, savannahs, etc.) are used. Large uncertainties relate to the extent of forest (32.0–42.5 million km^2) and grazing land (39–62 million km^2), due to discrepancies in definitions and observation methods (Luyssaert et al. 2014; Erb et al. 2017; Putz and Redford 2010; Schepaschenko et al. 2015; Birdsey and Pan 2015; FAO 2015a; Chazdon et al. 2016a; FAO 2018a). Infrastructure areas (including settlements, transportation and mining), while being almost negligible in terms of extent, represent particularly pervasive land-use activities, with far-reaching ecological, social and economic implications (Cherlet et al. 2018; Laurance et al. 2014).

The large imprint of humans on the land surface has led to the definition of anthromes, i.e. large-scale ecological patterns created by the sustained interactions between social and ecological drivers. The dynamics of these 'anthropogenic biomes' are key for land-use impacts as well as for the design of integrated response options (Ellis and Ramankutty 2008; Ellis et al. 2010; Cherlet et al. 2018; Ellis et al. 2010) (Chapter 6).

The intensity of land use varies hugely within and among different land-use types and regions. Averaged globally, around 10% of the ice-free land surface was estimated to be intensively managed (such as tree plantations, high livestock density grazing, large agricultural inputs), two-thirds moderately and the remainder at low intensities (Erb et al. 2016a). Practically all cropland is fertilised, with large regional variations. Irrigation is responsible for 70% of ground- or surface-water withdrawals by humans (Wisser et al. 2008; Chaturvedi et al. 2015; Siebert et al. 2015; FAOSTAT 2018). Humans appropriate one-quarter to one-third of the total potential net primary production (NPP), i.e. the NPP that would prevail in the absence of land use (estimated at about 60 GtC yr^{-1}; Bajželj et al. 2014; Haberl et al. 2014), about equally through biomass harvest and changes in NPP due to land management. The current total of agricultural (cropland and grazing) biomass harvest is estimated at about 6 GtC yr^{-1}, around 50–60% of this is consumed by livestock. Forestry harvest for timber and wood fuel amounts to about 1 GtC yr^{-1} (Alexander et al. 2017; Bodirsky and Müller 2014; Lassaletta et al. 2014, 2016; Mottet et al. 2017; Haberl et al. 2014; Smith et al. 2014; Bais et al. 2015; Bajželj et al. 2014) (Cross-Chapter Box 7 in Chapter 6).

1.1.2.3 Past and ongoing trends

Globally, cropland area changed by +15% and the area of permanent pastures by +8% since the early 1960s (FAOSTAT 2018), with strong regional differences (Figure 1.3). In contrast, cropland production since 1961 increased by about 3.5 times, the production of animal products by 2.5 times, and forestry by 1.5 times; in parallel with strong yield (production per unit area) increases (FAOSTAT 2018) (Figure 1.3). Per capita calorie supply increased by 17% since 1970 (Kastner et al. 2012), and diet composition changed markedly, tightly associated with economic development and lifestyle: since the early 1960s, per capita dairy product consumption increased by a factor of 1.2, and meat and vegetable oil consumption more than doubled (FAO 2017, 2018b; Tilman and Clark 2014; Marques et al. 2019). Population and livestock production represent key drivers of the global expansion of cropland for food production, only partly compensated by yield increases at the global level (Alexander et al. 2015). A number of studies have reported reduced growth rates or stagnation in yields in some regions in the last decades (*medium evidence, high agreement*; Lin and Huybers 2012; Ray et al. 2012; Elbehri, Aziz, Joshua Elliott 2015) (Section 5.2.2).

The past increases in agricultural production have been associated with strong increases in agricultural inputs (Foley et al. 2011; Siebert et al. 2015; Lassaletta et al. 2016) (Figures 1.1 and 1.3). Irrigation area doubled, total nitrogen fertiliser use increased by 800% (FAOSTAT 2018; IFASTAT 2018) since the early 1960s. Biomass trade volumes grew by a factor of nine (in tonnes dry matter yr^{-1}) in this period, which is much stronger than production (FAOSTAT 2018), resulting in a growing spatial disconnect between regions of production and consumption (Friis et al. 2016; Friis and Nielsen 2017; Schröter et al. 2018; Liu et al. 2013; Krausmann and Langthaler 2019). Urban and other infrastructure areas expanded by a factor of two since 1960 (Krausmann et al. 2013), resulting in disproportionally large losses of highly fertile cropland (Seto and Reenberg 2014; Martellozzo et al. 2015; Bren d'Amour et al. 2016; Seto and Ramankutty 2016; van Vliet et al. 2017). World regions show distinct patterns of change (Figure 1.3).

While most pastureland expansion replaced natural grasslands, cropland expansion replaced mainly forests (Ramankutty et al. 2018; Ordway et al. 2017; Richards and Friess 2016). Noteworthy large conversions occurred in tropical dry woodlands and savannahs, for example, in the Brazilian Cerrado (Lehmann and Parr 2016; Strassburg et al. 2017), the South American Caatinga and Chaco regions (Parr et al. 2014; Lehmann and Parr 2016) or African savannahs (Ryan et al. 2016). More than half of the original 4.3–12.6 million km^2 global wetlands (Erb et al. 2016a; Davidson 2014; Dixon et al. 2016) have been drained; since 1970 the wetland extent index, developed by aggregating data field-site time series that report changes in local inland wetland area, indicates a decline of more than 30% (Darrah et al. 2019) (Figure 1.1 and Section 4.2.1). Likewise, one-third of the estimated global area that in a non-used state would be covered in forests (Erb et al. 2017) has been converted to agriculture.

Global forest area declined by 3% since 1990 (about –5% since 1960) and continues to do so (FAO 2015a; Keenan et al. 2015; MacDicken et al. 2015; FAO 1963; Figure 1.1), but uncertainties are large. *Low agreement* relates to the concomitant trend of global tree cover. Some remote-sensing based assessments show global net-losses of forest or tree cover (Li et al. 2016; Nowosad et al. 2018; Hansen et al. 2013); others indicate a net gain (Song et al. 2018). Tree-cover gains would be in line with observed and modelled increases in photosynthetic active tissues ('greening'; Chen et al. 2019; Zhu et al. 2016; Zhao et al. 2018; de Jong et al. 2013; Pugh et al. 2019; De Kauwe et al. 2016; Kolby Smith et al. 2015) (Box 2.3 in Chapter 2), but *confidence* remains *low* whether gross forest or tree-cover gains are

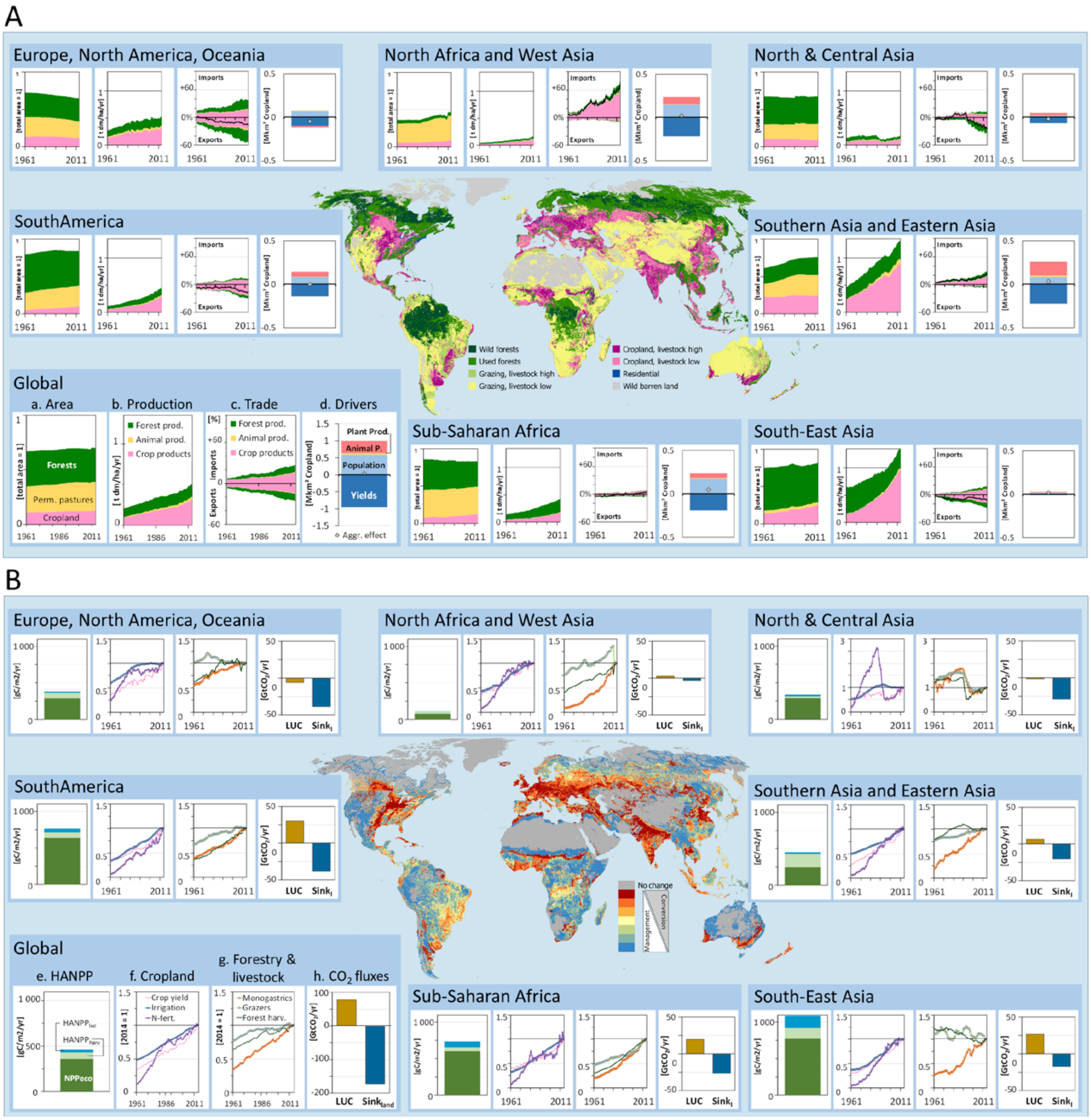

Figure 1.3 | Status and trends in the global land system: A. Trends in area, production and trade, and drivers of change. The map shows the global pattern of land systems (combination of maps Nachtergaele (2008); Ellis et al. (2010); Potapov et al. (2017); FAO's Animal Production and Health Division (2018); livestock low/high relates to low or high livestock density, respectively). The inlay figures show, for the globe and seven world regions, from left to right: (a) Cropland, permanent pastures and forest (used and unused) areas, standardised to total land area, (b) production in dry matter per year per total land area, (c) trade in dry matter in percent of total domestic production, all for 1961 to 2014 (data from FAOSTAT (2018) and FAO (1963) for forest area 1961). (d) drivers of cropland for food production between 1994 and 2011 (Alexander et al. 2015). See panel "global" for legend. "Plant Produc., Animal P.": changes in consumption of plant-based products and animal-products, respectively. **B.** Selected land-use pressures and impacts. The map shows the ratio between impacts on biomass stocks of land-cover conversions and of land management (changes that occur with land-cover types; only changes larger than 30 gC m^{-2} displayed; Erb et al. 2017), compared to the biomass stocks of the potential vegetation (vegetation that would prevail in the absence of land use, but with current climate). The inlay figures show, from left to right (e) the global Human Appropriation of Net Primary production (HANPP) in the year 2005, in gC m^{-2} yr^{-1} (Krausmann et al. 2013). The sum of the three components represents the NPP of the potential vegetation and consist of: (i) NPP_{eco}, i.e. the amount of NPP remaining in ecosystem after harvest, (ii) $HANPP_{harv}$, i.e. NPP harvested or killed during harvest, and (iii) $HANPP_{luc}$, i.e. NPP foregone due to land-use change. The sum of NPP_{eco} and $HANPP_{harv}$ is the NPP of the actual vegetation (Haberl et al. 2014; Krausmann et al. 2013). The two central inlay figures show changes in land-use intensity, standardised to 2014, related to (f) cropland (yields, fertilisation, irrigated area) and (g) forestry harvest per forest area, and grazers and monogastric livestock density per agricultural area (FAOSTAT 2018). (h) Cumulative CO_2 fluxes between land and the atmosphere between 2000 and 2014. LUC: annual CO_2 land use flux due to changes in land cover and forest management; $Sink_{land}$: the annual CO_2 land sink caused mainly by the indirect anthropogenic effects of environmental change (e.g, climate change and the fertilising effects of rising CO_2 and N concentrations), excluding impacts of land-use change (Le Quéré et al. 2018) (Section 2.3).

as large, or larger, than losses. This uncertainty, together with poor information on forest management, affects estimates and attribution of the land carbon sink (Sections 2.3, 4.3 and 4.6). Discrepancies are caused by different classification schemes and applied thresholds (e.g., minimum tree height and tree-cover thresholds used to define a forest), the divergence of forest and tree cover, and differences in methods and spatiotemporal resolution (Keenan et al. 2015; Schepaschenko et al. 2015; Bastin et al. 2017; Sloan and Sayer 2015; Chazdon et al. 2016a; Achard et al. 2014). However, there is *robust evidence* and *high agreement* that a net loss of forest and tree cover prevails in the tropics and a net gain, mainly of secondary, semi-natural and planted forests, in the temperate and boreal zones.

The observed regional and global historical land-use trends result in regionally distinct patterns of C fluxes between land and the atmosphere (Figure 1.3B). They are also associated with declines in biodiversity, far above background rates (Ceballos et al. 2015; De Vos et al. 2015; Pimm et al. 2014; Newbold et al. 2015; Maxwell et al. 2016; Marques et al. 2019). Biodiversity losses from past global land-use change have been estimated to be about 8–14%, depending on the biodiversity indicator applied (Newbold et al. 2015; Wilting et al. 2017; Gossner et al. 2016; Newbold et al. 2018; Paillet et al. 2010). In future, climate warming has been projected to accelerate losses of species diversity rapidly (Settele et al. 2014; Urban et al. 2016; Scholes et al. 2018; Fischer et al. 2018; Hoegh-Guldberg et al. 2018). The concomitance of land-use and climate change pressures render ecosystem restoration a key challenge (Anderson-Teixeira 2018; Yang et al. 2019) (Sections 4.8 and 4.9).

1.2 Key challenges related to land use change

1.2.1 Land system change, land degradation, desertification and food security

1.2.1.1 Future trends in the global land system

Human population is projected to increase to nearly 9.8 (± 1) billion people by 2050 and 11.2 billion by 2100 (United Nations 2018). More people, a growing global middle class (Crist et al. 2017), economic growth, and continued urbanisation (Jiang and O'Neill 2017) increase the pressures on expanding crop and pasture area and intensifying land management. Changes in diets, efficiency and technology could reduce these pressures (Billen et al. 2015; Popp et al. 2016; Muller et al. 2017; Alexander et al. 2015; Springmann et al. 2018; Myers et al. 2017; Erb et al. 2016c; FAO 2018b) (Sections 5.3 and 6.2.2).

Given the large uncertainties underlying the many drivers of land use, as well as their complex relation to climate change and other biophysical constraints, future trends in the global land system are explored in scenarios and models that seek to span across these uncertainties (Cross-Chapter Box 1 in Chapter 1). Generally, these scenarios indicate a continued increase in global food demand, owing to population growth and increasing wealth. The associated land area needs are a key uncertainty, a function of the interplay between production, consumption, yields, and production efficiency (in particular for livestock and waste) (FAO 2018b; van Vuuren et al. 2017; Springmann et al. 2018; Riahi et al. 2017; Prestele et al. 2016; Ramankutty et al. 2018; Erb et al. 2016b; Popp et al. 2016) (Section 1.3 and Cross-Chapter Box 1 in Chapter 1). Many factors, such as climate change, local contexts, education, human and social capital, policy-making, economic framework conditions, energy availability, degradation, and many more, affect this interplay, as discussed in all chapters of this report.

Global telecouplings in the land system, the distal connections and multidirectional flows between regions and land systems, are expected to increase, due to urbanisation (Seto et al. 2012; van Vliet et al. 2017; Jiang and O'Neill 2017; Friis et al. 2016), and international trade (Konar et al. 2016; Erb et al. 2016b; Billen et al. 2015; Lassaletta et al. 2016). Telecoupling can support efficiency gains in production, but can also lead to complex cause–effect chains and indirect effects such as land competition or leakage (displacement of the environmental impacts; see Glossary), with governance challenges (Baldos and Hertel 2015; Kastner et al. 2014; Liu et al. 2013; Wood et al. 2018; Schröter et al. 2018; Lapola et al. 2010; Jadin et al. 2016; Erb et al. 2016b; Billen et al. 2015; Chaudhary and Kastner 2016; Marques et al. 2019; Seto and Ramankutty 2016) (Section 1.2.1.5). Furthermore, urban growth is anticipated to occur at the expense of fertile (crop)land, posing a food security challenge, in particular in regions of high population density and agrarian-dominated economies, with limited capacity to compensate for these losses (Seto et al. 2012; Güneralp et al. 2013; Aronson et al. 2014; Martellozzo et al. 2015; Bren d'Amour et al. 2016; Seto and Ramankutty 2016; van Vliet et al. 2017).

Future climate change and increasing atmospheric CO_2 concentration are expected to accentuate existing challenges by, for example, shifting biomes or affecting crop yields (Baldos and Hertel 2015; Schlenker and Lobell 2010; Lipper et al. 2014; Challinor et al. 2014; Myers et al. 2017) (Section 5.2.2), as well as through land-based climate change mitigation. There is *high confidence* that large-scale implementation of bioenergy or afforestation can further exacerbate existing challenges (Smith et al. 2016) (Section 1.3.1 and Cross-Chapter Box 7 in Chapter 6).

1.2.1.2 Land degradation

As discussed in Chapter 4, the concept of land degradation, including its definition, has been used in different ways in different communities and in previous assessments (such as the IPBES Land Degradation and Restoration Assessment). In the SRCCL, land degradation is defined as a *negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans*. This definition applies to forest and non-forest land (Chapter 4 and Glossary).

Land degradation is a critical issue for ecosystems around the world due to the loss of actual or potential productivity or utility (Ravi et al. 2010; Mirzabaev et al. 2015; FAO and ITPS 2015; Cerretelli et al. 2018). Land degradation is driven to a large degree by unsustainable agriculture and forestry, socio-economic pressures, such as rapid urbanisation and population growth, and unsustainable production practices in combination with climatic factors (Field et al. 2014b; Lal 2009; Beinroth et al. 1994; Abu Hammad and Tumeizi 2012; Ferreira et al. 2018; Franco and Giannini 2005; Abahussain et al. 2002).

Global estimates of the total degraded area vary from less than 10 million km^2 to over 60 million km^2, with additionally large disagreement regarding the spatial distribution (Gibbs and Salmon 2015) (Section 4.3). The annual increase in the degraded land area has been estimated as 50,000–100,000 million km^2 yr^{-1} (Stavi and Lal 2015), and the loss of total ecosystem services equivalent to about 10% of the world's GDP in the year 2010 (Sutton et al. 2016). Although land degradation is a common risk across the globe, poor countries remain most vulnerable to its impacts. Soil degradation is of particular concern, due to the long period necessary to restore soils (Lal 2009; Stockmann et al. 2013; Lal 2015), as well as the rapid degradation of primary forests through fragmentation (Haddad et al. 2015). Among the most vulnerable ecosystems to degradation are high-carbon-stock wetlands (including peatlands). Drainage of natural wetlands for use in agriculture leads to high CO_2 emissions and degradation (*high confidence*) (Strack 2008; Limpens et al. 2008; Aich et al. 2014; Murdiyarso et al. 2015; Kauffman et al. 2016; Dohong et al. 2017; Arifanti et al. 2018; Evans et al. 2019). Land degradation is an important factor contributing to uncertainties in the mitigation potential of land-based ecosystems (Smith et al. 2014). Furthermore, degradation that reduces forest (and agricultural) biomass and soil organic carbon leads to higher rates of runoff (*high confidence*) (Molina et al. 2007; Valentin et al. 2008; Mateos et al. 2017; Noordwijk et al. 2017) and hence to increasing flood risk (*low confidence*) (Bradshaw et al. 2007; Laurance 2007; van Dijk et al. 2009).

1.2.1.3 Desertification

The SRCCL adopts the definition of the UNCCD of desertification, being land degradation in arid, semi-arid and dry sub-humid areas (drylands) (Glossary and Section 3.1.1). Desertification results from various factors, including climate variations and human activities, and is not limited to irreversible forms of land degradation (Tal 2010; Bai et al. 2008). A critical challenge in the assessment of desertification is to identify a 'non-desertified' reference state (Bestelmeyer et al. 2015). While climatic trends and variability can change the intensity of desertification processes, some authors exclude climate effects, arguing that desertification is a purely human-induced process of land degradation with different levels of severity and consequences (Sivakumar 2007).

As a consequence of varying definitions and different methodologies, the area of desertification varies widely (D'Odorico et al. 2013; Bestelmeyer et al. 2015; and references therein). Arid regions of the world cover up to about 46% of the total terrestrial surface (about 60 million km^2) (Pravalie 2016; Koutroulis 2019). Around 3 billion people reside in dryland regions (D'Odorico et al. 2013; Maestre et al. 2016) (Section 3.1.1). In 2015, about 500 (360–620) million people lived within areas which experienced desertification between 1980s and 2000s (Figure 1.1and Section 3.1.1). The combination of low rainfall with frequently infertile soils renders these regions, and the people who rely on them, vulnerable to both climate change, and unsustainable land management (*high confidence*). In spite of the national, regional and international efforts to combat desertification, it remains one of the major environmental problems (Abahussain et al. 2002; Cherlet et al. 2018).

1.2.1.4 Food security, food systems and linkages to land-based ecosystems

The High Level Panel of Experts of the Committee on Food Security define the food system as to "gather all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes" (HLPE 2017). Likewise, food security has been defined as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 2017). By this definition, food security is characterised by food availability, economic and physical access to food, food utilisation and food stability over time. Food and nutrition security is one of the key outcomes of the food system (FAO 2018b; Figure 1.4).

After a prolonged decline, world hunger appears to be on the rise again, with the number of undernourished people having increased to an estimated 821 million in 2017, up from 804 million in 2016 and 784 million in 2015, although still below the 900 million reported in 2000 (FAO et al. 2018) (Section 5.1.2). Of the total undernourished in 2018, for example, 256.5 million lived in Africa, and 515.1 million in Asia (excluding Japan). The same FAO report also states that child undernourishment continues to decline, but levels of overweight populations and obesity are increasing. The total number of overweight children in 2017 was 38–40 million worldwide, and globally up to around two billion adults are by now overweight (Section 5.1.2). FAO also estimated that close to 2000 million people suffer from micronutrient malnutrition (FAO 2018b).

Food insecurity most notably occurs in situations of conflict, and conflict combined with droughts or floods (Cafiero et al. 2018; Smith et al. 2017). The close parallel between food insecurity prevalence and poverty means that tackling development priorities would enhance sustainable land use options for climate mitigation.

Climate change affects the food system as changes in trends and variability in rainfall and temperature variability impact crop and livestock productivity and total production (Osborne and Wheeler 2013; Tigchelaar et al. 2018; Iizumi and Ramankutty 2015), the nutritional quality of food (Loladze 2014; Myers et al. 2014; Ziska et al. 2016; Medek et al. 2017), water supply (Nkhonjera 2017), and incidence of pests and diseases (Curtis et al. 2018). These factors also impact on human health, increasing morbidity and affecting human ability to process ingested food (Franchini and Mannucci 2015; Wu et al. 2016; Raiten and Aimone 2017). At the same time, the food system generates negative externalities (the environmental effects of production and consumption) in the form of GHG emissions

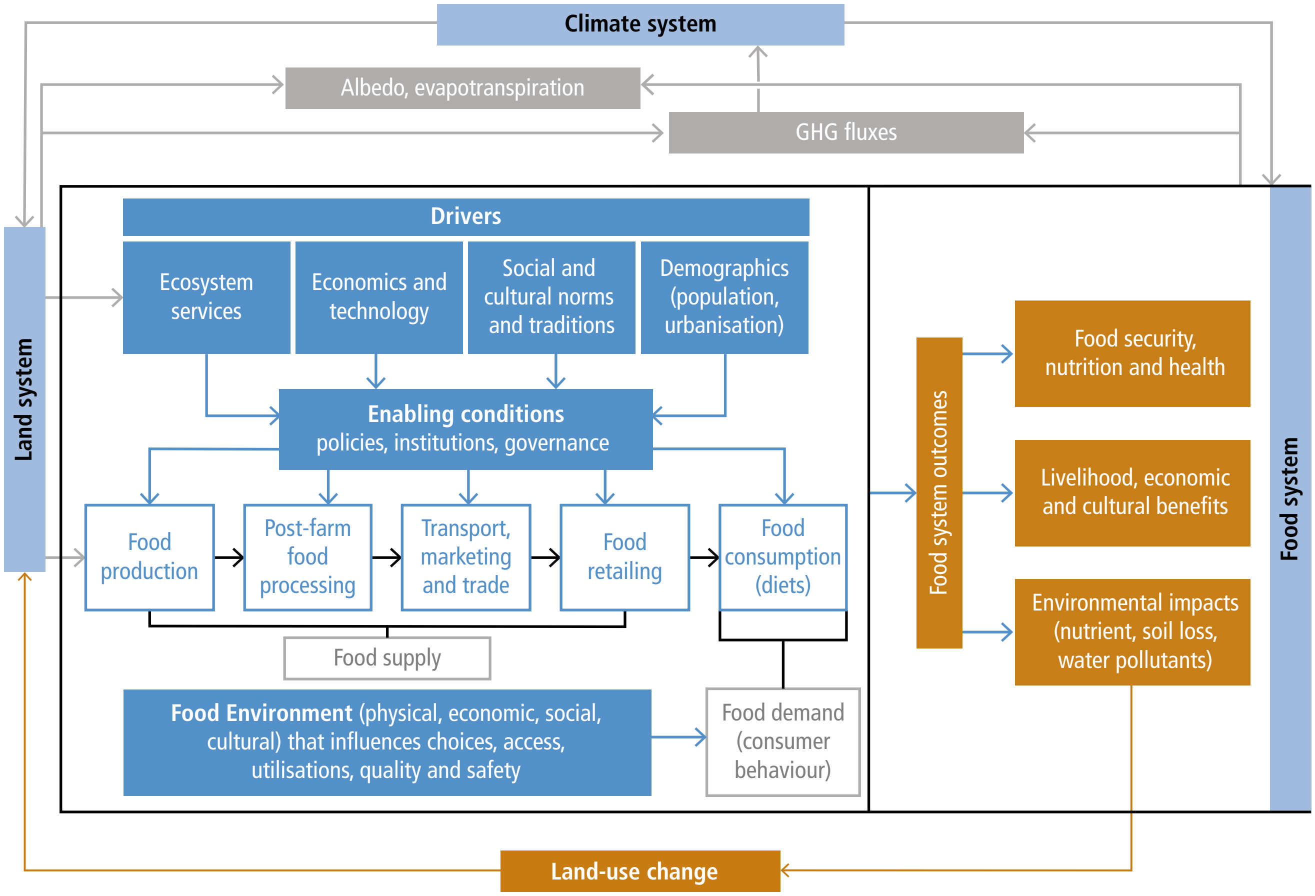

Figure 1.4 | Food system (and its relations to land and climate): The food system is conceptualised through supply (production, processing, marketing and retailing) and demand (consumption and diets) that are shaped by physical, economic, social and cultural determinants influencing choices, access, utilisation, quality, safety and waste. Food system drivers (ecosystem services, economics and technology, social and cultural norms and traditions, and demographics) combine with the enabling conditions (policies, institutions and governance) to affect food system outcomes including food security, nutrition and health, livelihoods, economic and cultural benefits as well as environmental outcomes or side-effects (nutrient and soil loss, water use and quality, GHG emissions and other pollutants). Climate and climate change have direct impacts on the food system (productivity, variability, nutritional quality) while the latter contributes to local climate (albedo, evapotranspiration) and global warming (GHGs). The land system (function, structures, and processes) affects the food system directly (food production) and indirectly (ecosystem services) while food demand and supply processes affect land (land-use change) and land-related processes (e.g., land degradation, desertification) (Chapter 5).

(Sections 1.1.2 and 2.3), pollution (van Noordwijk and Brussaard 2014; Thyberg and Tonjes 2016; Borsato et al. 2018; Kibler et al. 2018), water quality (Malone et al. 2014; Norse and Ju 2015), and ecosystem services loss (Schipper et al. 2014; Eeraerts et al. 2017) with direct and indirect impacts on climate change and reduced resilience to climate variability. As food systems are assessed in relation to their contribution to global warming and/or to land degradation (e.g., livestock systems) it is critical to evaluate their contribution to food security and livelihoods and to consider alternatives, especially for developing countries where food insecurity is prevalent (Röös et al. 2017; Salmon et al. 2018).

1.2.1.5 Challenges arising from land governance

Land-use change has both positive and negative effects: it can lead to economic growth, but it can become a source of tension and social unrest leading to elite capture, and competition (Haberl 2015). Competition for land plays out continuously among different use types (cropland, pastureland, forests, urban spaces, and conservation and protected lands) and between different users within the same land-use category (subsistence vs commercial farmers) (Dell'Angelo et al. 2017b). Competition is mediated through economic and market forces (expressed through land rental and purchases, as well as trade and investments). In the context of such transactions, power relations often disfavour disadvantaged groups such as small-scale farmers, indigenous communities or women (Doss et al. 2015; Ravnborg et al. 2016). These drivers are influenced to a large degree by policies, institutions and governance structures. Land governance determines not only who can access the land, but also the role of land ownership (legal, formal, customary or collective) which influences land use, land-use change and the resulting land competition (Moroni 2018).

Globally, there is competition for land because it is a finite resource and because most of the highly productive land is already exploited by humans (Lambin and Meyfroidt 2011; Lambin 2012; Venter et al. 2016). Driven by growing population, urbanisation, demand for food and energy, as well as land degradation, competition for land is expected to accentuate land scarcity in the future (Tilman et al. 2011; Foley et al. 2011; Lambin 2012; Popp et al. 2016) (*robust evidence, high agreement*). Climate change influences land use both directly and indirectly, as climate policies can also a play a role in increasing land competition via forest conservation policies, afforestation, or energy crop production (Section 1.3.1), with the potential for implications for food security (Hussein et al. 2013) and local land-ownership.

An example of large-scale change in land ownership is the much-debated large-scale land acquisition (LSLA) by investors which peaked in 2008 during the food price crisis, the financial crisis, and has also been linked to the search for biofuel investments (Dell'Angelo et al. 2017a). Since 2000, almost 50 million hectares of land have been acquired, and there are no signs of stagnation in the foreseeable future (Land Matrix 2018). The LSLA phenomenon, which largely targets agriculture, is widespread, including Sub-Saharan Africa, Southeast Asia, Eastern Europe and Latin America (Rulli et al. 2012; Nolte et al. 2016; Constantin et al. 2017). LSLAs are promoted by investors and host governments on economic grounds (infrastructure, employment, market development) (Deininger et al. 2011), but their social and environmental impacts can be negative and significant (Dell'Angelo et al. 2017a).

Much of the criticism of LSLA focuses on its social impacts, especially the threat to local communities' land rights (especially indigenous people and women) (Anseeuw et al. 2011) and displaced communities creating secondary land expansion (Messerli et al. 2014; Davis et al. 2015). The promises that LSLAs would develop efficient agriculture on non-forested, unused land (Deininger et al. 2011) has so far not been fulfilled. However, LSLA is not the only outcome of weak land governance structures (Wang et al. 2016): other forms of inequitable or irregular land acquisition can also be home-grown, pitting one community against a more vulnerable group (Xu 2018) or land capture by urban elites (McDonnell 2017). As demands on land are increasing, building governance capacity and securing land tenure becomes essential to attain sustainable land use, which has the potential to mitigate climate change, promote food security, and potentially reduce risks of climate-induced migration and associated risks of conflicts (Section 7.6).

1.2.2 Progress in dealing with uncertainties in assessing land processes in the climate system

1.2.2.1 Concepts related to risk, uncertainty and confidence

In context of the SRCCL, risk refers to the potential for the adverse consequences for human or (land-based) ecological systems, arising from climate change or responses to climate change. Risk related to climate change impacts integrates across the hazard itself, the time of exposure and the vulnerability of the system; the assessment of all three of these components, their interactions and outcomes, is uncertain (see Glossary for expanded definition, and Section 7.1.2). For instance, a risk to human society is the continued loss of productive land which might arise from climate change, mismanagement, or a combination of both factors. However, risk can also arise from the potential for adverse consequences from responses to climate change, such as widespread deployment of bioenergy which is intended to reduce GHG emissions and thus limit climate change, but can present its own risks to food security (Chapters 5–7).

Demonstrating with some statistical certainty that the climate or the land system affected by climate or land use has changed (detection), and evaluating the relative contributions of multiple causal factors to that change (with a formal assessment of confidence (attribution); see Glossary) remain challenging aspects in both observations and models (Rosenzweig and Neofotis 2013; Gillett et al. 2016; Lean 2018). Uncertainties arising for example, from missing or imprecise data, ambiguous terminology, incomplete process representation in models, or human decision-making contribute to these challenges, and some examples are provided in this subsection. In order to reflect various sources of uncertainties in the state of scientific understanding, IPCC assessment reports provide estimates of confidence (Mastrandrea et al. 2011). This confidence language is also used in the SRCCL (Figure 1.5).

1.2.2.2 Nature and scope of uncertainties related to land use

Identification and communication of uncertainties is crucial to support decision making towards sustainable land management. Providing a robust, and comprehensive understanding of uncertainties in observations, models and scenarios is a fundamental first step in the IPCC confidence framework (see above). This will remain a challenge in future, but some important progress has been made over recent years.

Uncertainties in observations

The detection of changes in vegetation cover and structural properties underpins the assessment of land-use change, degradation and desertification. It is continuously improving by enhanced Earth observation capacity (Hansen et al. 2013; He et al. 2018; Ardö et al. 2018; Spennemann et al. 2018) (see also Table SM.1.1 in Supplementary Material). Likewise, the picture of how soil organic carbon, and GHG and water fluxes, respond to land-use change and land management continues to improve through advances in methodologies and sensors (Kostyanovsky et al. 2018; Brümmer et al. 2017; Iwata et al. 2017; Valayamkunnath et al. 2018). In both cases, the relative shortness of the record, data gaps, data treatment algorithms and – for remote sensing – differences in the definitions of major vegetation-cover classes limit the detection of trends (Alexander et al. 2016a; Chen et al. 2014; Yu et al. 2014; Lacaze et al. 2015; Song 2018; Peterson et al. 2017). In many developing countries, the cost of satellite remote sensing remains a challenge, although technological advances are starting to overcome this problem (Santilli et al. 2018), while ground-based observations networks are often not available.

Integration of multiple data sources in model and data assimilation schemes reduces uncertainties (Li et al. 2017; Clark et al. 2017; Lees et al. 2018), which might be important for the advancement of early warning systems. Early warning systems are a key feature of short-term (i.e. seasonal) decision-support systems and are becoming increasingly important for sustainable land management and food security (Shtienberg 2013; Jarroudi et al. 2015) (Sections 6.2.3 and 7.4.3). Early warning systems can help to optimise fertiliser and water use, aid disease suppression, and/or increase the economic benefit by enabling strategic farming decisions on when and what to plant (Caffi et al. 2012; Watmuff et al. 2013; Jarroudi et al. 2015; Chipanshi et al. 2015). Their suitability depends on the capability of the methods to accurately predict crop or pest developments, which in turn depends on expert agricultural knowledge, and the accuracy of

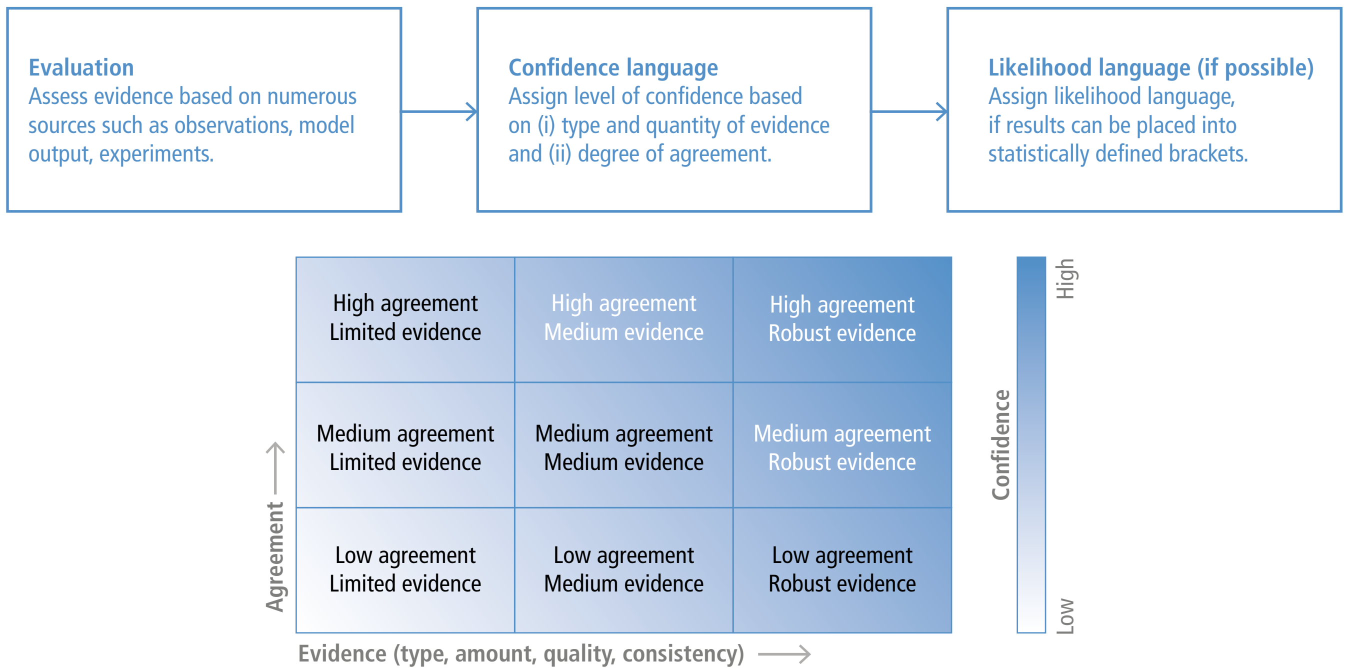

Figure 1.5 | Use of confidence language.

the weather data used to run phenological models (Caffi et al. 2012; Shtienberg 2013).

Uncertainties in models

Model intercomparison is a widely used approach to quantify some sources of uncertainty in climate change, land-use change and ecosystem modelling, often associated with the calculation of model-ensemble medians or means (see e.g., Sections 2.2 and 5.2). Even models of broadly similar structure differ in their projected outcome for the same input, as seen for instance in the spread in climate change projections from Earth System Models (ESMs) to similar future anthropogenic GHG emissions (Parker 2013; Stocker et al. 2013a). These uncertainties arise, for instance, from different parameter values, different processes represented in models, or how these processes are mathematically described. If the outputs of ESM simulations are used as input to impact models, these uncertainties can propagate to projected impacts (Ahlstrom et al. 2013).

Thus, the increased quantification of model performance in benchmarking exercises (the repeated confrontation of models with observations to establish a track-record of model developments and performance) is an important development to support the design and the interpretation of the outcomes of model ensemble studies (Randerson et al. 2009; Luo et al. 2012; Kelley et al. 2013). Since observational datasets in themselves are uncertain, benchmarking benefits from transparent information on the observations that are used, and the inclusion of multiple, regularly updated data sources (Luo et al. 2012; Kelley et al. 2013). Improved benchmarking approaches and the associated scoring of models may support weighted model means contingent on model performance. This could be an important step forward when calculating ensemble means across a range of models (Buisson et al. 2009; Parker 2013; Prestele et al. 2016).

Uncertainties arising from unknown futures

Large differences exist in projections of future land-cover change, both between and within scenario projections (Fuchs et al. 2015; Eitelberg et al. 2016; Popp et al. 2016; Krause et al. 2017; Alexander et al. 2016a). These differences reflect the uncertainties associated with baseline data, thematic classifications, different model structures and model parameter estimation (Alexander et al. 2017a; Prestele et al. 2016; Cross-Chapter Box 1 in Chapter 1). Likewise, projections of future land-use change are also highly uncertain, reflecting – among other factors – the absence of important crop, pasture and management processes in Integrated Assessment Models (Rose 2014) (Cross-Chapter Box 1 in Chapter 1) and in models of the terrestrial carbon cycle (Arneth et al. 2017). These processes have been shown to have large impacts on carbon stock changes (Arneth et al. 2017). Common scenario frameworks are used to capture the range of future uncertainties in scenarios. The most commonly used recent framework in climate change studies is based on the Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) (Popp et al. 2016; Riahi et al. 2017). The RCPs prescribe levels of radiative forcing (W m^{-2}) arising from different atmospheric concentrations of GHGs that lead to different levels of climate change. For example, RCP2.6 (2.6 W m^{-2}) is projected to lead to global mean temperature changes of about 0.9°C–2.3°C, and RCP8.5 (8.5 W m^{-2}) to global mean temperature changes of about 3.2°C–5.4°C (van Vuuren et al. 2014).

The SSPs describe alternative trajectories of future socio-economic development with a focus on challenges to climate mitigation and challenges to climate adaptation (O'Neill et al. 2014). SSP1 represents a sustainable and cooperative society with a low-carbon economy and high capacity to adapt to climate change. SSP3 has social inequality that entrenches reliance on fossil fuels and limits adaptive capacity. SSP4 has large differences in income within and across world regions; it facilitates low-carbon economies in places, but limits adaptive capacity everywhere. SSP5 is a technologically advanced world with a strong economy that is heavily dependent on fossil fuels, but with high adaptive capacity. SSP2 is an intermediate case between SSP1 and SSP3 (O'Neill et al. 2014). The SSPs are commonly used with models to project future land-use change (Cross-Chapter Box 1 in Chapter 1).

The SSPs map onto the RCPs through shared assumptions. For example, a higher level of climate change (RCP8.5) is associated with higher challenges for climate change mitigation (SSP5). Not all SSPs are, however, associated with all RCPs. For example, an SSP5 world is committed to high fossil fuel use, associated GHG emissions, and this is not easily commensurate with lower levels of climate change (e.g., RCP2.6). Engstrom et al. (2016) took this approach further by ascribing levels of probability that associate an SSP with an RCP, contingent on the SSP scenario assumptions (Cross-Chapter Box 1 in Chapter 1).

Cross-Chapter Box 1 | Scenarios and other methods to characterise the future of land

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About this box

The land-climate system is complex and future changes are uncertain, but methods exist (collectively known as *futures analysis*) to help decision-makers in navigating through this uncertainty. Futures analysis comprises a number of different and widely used methods, such as scenario analysis (Rounsevell and Metzger 2010), envisioning or target setting (Kok et al. 2018), pathways analysis (IPBES 2016; IPCC 2018),[1] and conditional probabilistic futures (Vuuren et al. 2018; Engstrom et al. 2016; Henry et al. 2018) (Table 1 in this Cross-Chapter Box). Scenarios and other methods to characterise the future can support a discourse with decision-makers about the sustainable development options that are available to them. All chapters of this assessment draw conclusions from futures analysis and so, the purpose of this box is to outline the principal methods used, their application domains, their uncertainties and their limitations.

Exploratory scenario analysis

Many exploratory scenarios are reported in climate and land system studies on climate change (Dokken 2014), such as related to land-based, climate change mitigation via reforestation/afforestation, avoided deforestation or bioenergy (Kraxner et al. 2013; Humpenoder et al. 2014; Krause et al. 2017) and climate change impacts and adaptation (Warszawski et al. 2014). There are global-scale scenarios of food security (Foley et al. 2011; Pradhan et al. 2013, 2014), but fewer scenarios of desertification, land degradation and restoration (Wolff et al. 2018). Exploratory scenarios combine qualitative 'storylines' or descriptive narratives of the underlying causes (or drivers) of change (Nakicenovic and Swart 2000; Rounsevell and Metzger 2010; O'Neill et al. 2014) with quantitative projections from computer models. Different types of models are used for this purpose based on very different modelling paradigms, baseline data and underlying assumptions (Alexander et al. 2016a; Prestele et al. 2016). Figure 1 in this Cross-Chapter Box below outlines how a combination of models can quantify these components as well as the interactions between them.

Exploratory scenarios often show that socio-economic drivers have a larger effect on land-use change than climate drivers (Harrison et al. 2014, 2016). Of these, technological development is critical in affecting the production potential (yields) of food and bioenergy and the feed conversion efficiency of livestock (Rounsevell et al. 2006; Wise et al. 2014; Kreidenweis et al. 2018), as well as the area of land needed for food production (Foley et al. 2011; Weindl et al. 2017; Kreidenweis et al. 2018). Trends in consumption, for example, diets or waste reduction, are also fundamental in affecting land-use change (Pradhan et al. 2013; Alexander et al. 2016b; Weindl et al. 2017; Alexander et al. 2017; Vuuren et al. 2018; Bajželj et al. 2014). Scenarios of land-based mitigation through large-scale bioenergy production and afforestation often lead to negative trade-offs with food security (food prices), water resources and biodiversity (Cross-Chapter Box 7 in Chapter 6).

Many exploratory scenarios are based on common frameworks such as the Shared Socio-economic Pathways (SSPs) (Popp et al. 2016; Riahi et al. 2017; Doelman et al. 2018)) (Section 1.2). However, other methods are used. *Stylised scenarios* prescribe assumptions about climate and land-use change solutions, for example, dietary change, food waste reduction and afforestation areas

1 Different communities have a different understanding of the concept of pathways (IPCC 2018). Here, we refer to pathways as a description of the time-dependent actions required to move from today's world to a set of future visions (IPCC 2018). However, the term pathways is commonly used in the climate change literature as a synonym for projections or trajectories (e.g., shared socio-economic pathways).

Cross-Chapter Box 1 (continued)

(Pradhan et al. 2013, 2014; Kreidenweis et al. 2016; Rogelj et al. 2018b; Seneviratne et al. 2018; Vuuren et al. 2018). These scenarios provide useful thought experiments, but the feasibility of achieving the stylised assumptions is often unknown. *Shock scenarios* explore the consequences of low probability, high-impact events such as pandemic diseases, cyber-attacks and failures in food supply chains (Challinor et al. 2018), often in food security studies. Because of the diversity of exploratory scenarios, attempts have been made to categorise them into 'archetypes' based on the similarity between their assumptions in order to facilitate communication (IPBES 2018a).

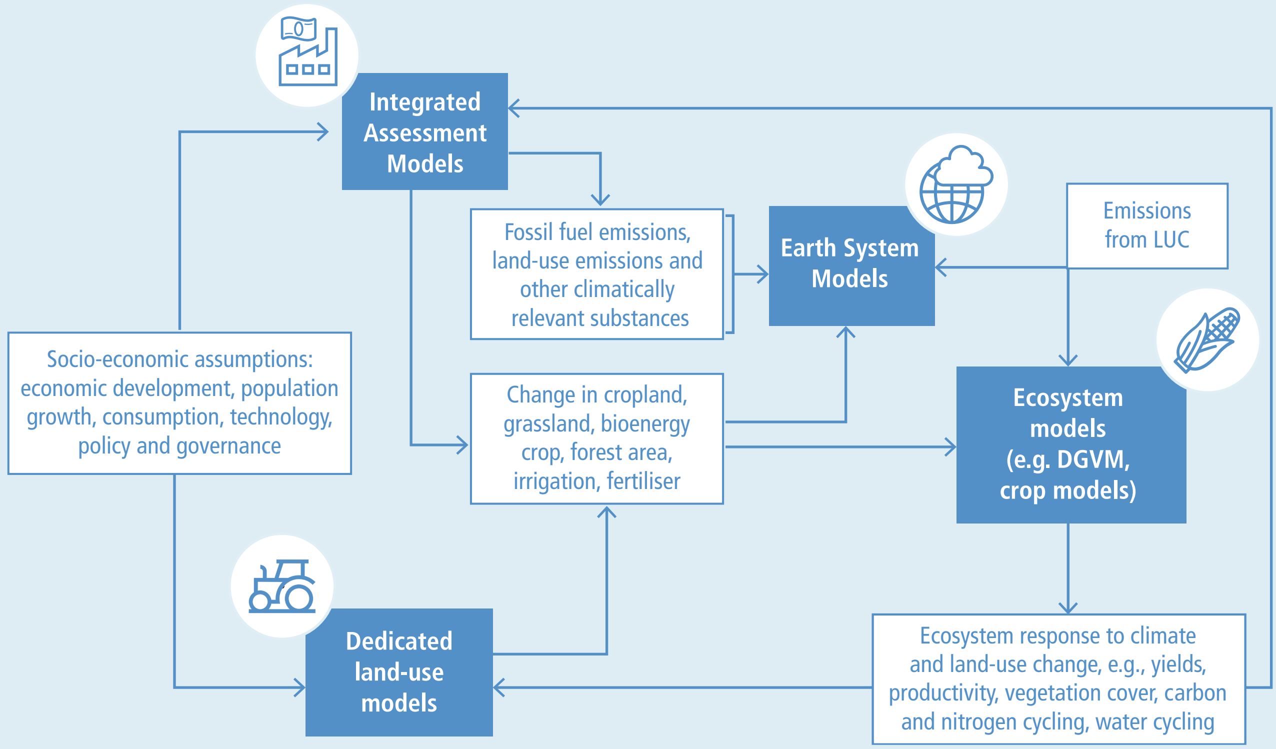
Conditional probabilistic futures explore the consequences of model parameter uncertainty in which these uncertainties are conditional on scenario assumptions (Neill 2004). Only a few studies have applied the conditional probabilistic approach to land-use futures (Brown et al. 2014; Engstrom et al. 2016; Henry et al. 2018). By accounting for uncertainties in key drivers these studies show large ranges in land-use change, for example, global cropland areas of 893–2380 Mha by the end of the 21st century (Engstrom et al. 2016). They also find that land-use targets may not be achieved, even across a wide range of scenario parameter settings, because of trade-offs arising from the competition for land (Henry et al. 2018; Heck et al. 2018). Accounting for uncertainties across scenario assumptions can lead to convergent outcomes for land-use change, which implies that certain outcomes are more robust across a wide range of uncertain scenario assumptions (Brown et al. 2014).

In addition to global scale scenario studies, sub-national studies demonstrate that regional climate change impacts on the land system are highly variable geographically because of differences in the spatial patterns of both climate and socio-economic change (Harrison et al. 2014). Moreover, the capacity to adapt to these impacts is strongly dependent on the regional, socio-economic context and coping capacity (Dunford et al. 2014); processes that are difficult to capture in global scale scenarios. Regional scenarios are often co-created with stakeholders through participatory approaches (Kok et al. 2014), which are powerful in reflecting diverse worldviews and stakeholder values. Stakeholder participatory methods provide additional richness and context to storylines, as well as providing salience and legitimacy for local stakeholders (Kok et al. 2014).

Cross-Chapter Box 1, Table 1 | Description of the principal methods used in land and climate futures analysis.

Futures method	Description and subtypes	Application domain	Time horizon	Examples in this assessment
Exploratory scenarios. Trajectories of change in system components from the present to contrasting, alternative futures based on plausible and internally consistent assumptions about the underlying drivers of change	*Long-term projections* quantified with models	Climate system, land system and other components of the environment (e.g., biodiversity, ecosystem functioning, water resources and quality), for example the SSPs	10–100 years	2.3, 2.6.2, 5.2.3, 6.1.4, 6.4.4, 7.2
	Business-as-usual scenarios (including 'outlooks')	A continuation into the future of current trends in key drivers to explore the consequences of these in the near term	5–10 years, 20–30 years for outlooks	1.2.1, 2.6.2, 5.3.4, 6.1.4
	Policy and planning scenarios (including business planning)	*Ex ante* analysis of the consequences of alternative policies or decisions based on known policy options or already implemented policy and planning measures	5–30 years	2.6.3, 5.5.2, 5.6.2, 6.4.4
	Stylised scenarios (with single and multiple options)	Afforestation/reforestation areas, bioenergy areas, protected areas for conservation, consumption patterns (e.g., diets, food waste)	10–100 years	2.6.1, 5.5.1, 5.5.2, 5.6.1, 5.6.2, 6.4.4, 7.2
	Shock scenarios (high impact single events)	Food supply chain collapses, cyberattacks, pandemic diseases (humans, crops and livestock)	Near-term events (up to 10 years) leading to long-term impacts (10–100 years)	5.8.1
	Conditional probabilistic futures ascribe probabilities to uncertain drivers that are conditional on scenario assumptions	Where some knowledge is known about driver uncertainties, for example, population, economic growth, land-use change	10–100 years	1.2
Normative scenarios. Desired futures or outcomes that are aspirational and how to achieve them	*Visions, goal-seeking or target-seeking scenarios*	Environmental quality, societal development, human well-being, the Representative Concentration Pathways (RCPs,) 1.5°C scenarios	5–10 years to 10–100 years	2.6.2, 6.4.4, 7.2, 5.5.2
	Pathways as alternative sets of choices, actions or behaviours that lead to a future vision (goal or target)	Socio-economic systems, governance and policy actions	5–10 years to 10–100 years	5.5.2, 6.4.4, 7.2

Cross-Chapter Box 1 (continued)



Cross-Chapter Box 1, Figure 1 | Interactions between land and climate system components and models in scenario analysis. The blue text describes selected model inputs and outputs.

Normative scenarios: visions and pathways analysis

Normative scenarios reflect a desired or target-seeking future. Pathways analysis is important in moving beyond the '*what if?*' perspective of exploratory scenarios to evaluate how normative futures might be achieved in practice, recognising that multiple pathways may achieve the same future vision. Pathways analysis focuses on consumption and behavioural changes through transitions and transformative solutions (IPBES 2018a). Pathways analysis is highly relevant in support of policy, since it outlines sets of time-dependent actions and decisions to achieve future targets, especially with respect to sustainable development goals, as well as highlighting trade-offs and co-benefits (IPBES 2018a). Multiple, alternative pathways have been shown to exist that mitigate trade-offs whilst achieving the priorities for future sustainable development outlined by governments and societal actors. Of these alternatives, the most promising focus on long-term societal transformations through education, awareness raising, knowledge sharing and participatory decision-making (IPBES 2018a).

What are the limitations of land-use scenarios?

Applying a common scenario framework (e.g., RCPs/SSPs) supports the comparison and integration of climate- and land-system scenarios, but a 'climate-centric' perspective can limit the capacity of these scenarios to account for a wider range of land-relevant drivers (Rosa et al. 2017). For example, in climate mitigation scenarios it is important to assess the impact of mitigation actions on the broader environment such as biodiversity, ecosystem functioning, air quality, food security, desertification/degradation and water cycles (Rosa et al. 2017). This implies the need for a more encompassing and flexible approach to creating scenarios that considers other environmental aspects, not only as a part of impact assessment, but also during the process of creating the scenarios themselves.

A limited number of models can quantify global scale, land-use change scenarios, and there is large variance in the outcomes of these models (Alexander et al. 2016a; Prestele et al. 2016). In some cases, there is greater variability between the models themselves than between the scenarios that they are quantifying, and these differences vary geographically (Prestele et al. 2016). These differences arise from variations in baseline datasets, thematic classes and modelling paradigms (Alexander et al. 2016a; Popp et al. 2016; Prestele et al. 2016). Model evaluation is critical in establishing confidence in the outcomes of modelled futures (Ahlstrom et al. 2012; Kelley et al. 2013). Some, but not all, land-use models are evaluated against observational data and model evaluation is rarely reported. Hence, there is a need for more transparency in land-use modelling, especially in evaluation and testing, as well as making model code available with complete sets of scenario outputs (e.g., Dietrich et al. 2018).

Cross-Chapter Box 1 (continued)

There is a small, but growing literature on quantitative pathways to achieve normative visions and their associated trade-offs (IPBES 2018a). Whilst the visions themselves may be clearly articulated, the societal choices, behaviours and transitions needed to attain them, are not. Better accounting for human behaviour and decision-making processes in global scale land-use models would improve the capacity to quantify pathways to sustainable futures (Rounsevell et al. 2014; Arneth et al. 2014; Calvin and Bond-Lamberty 2018). It is, however, difficult to understand and represent human behaviour and social interaction processes at global scales. Decision-making in global models is commonly represented through economic processes (Arneth et al. 2014). Other important human processes for land systems including equity, fairness, land tenure and the role of institutions and governance, receive less attention, and this limits the use of global models to quantify transformative pathways, adaptation and mitigation (Arneth et al. 2014; Rounsevell et al. 2014; Wang et al. 2016). No model exists at present to represent complex human behaviours at the global scale, although the need has been highlighted (Rounsevell et al. 2014; Arneth et al. 2014; Robinson et al. 2017; Brown et al. 2017; Calvin and Bond-Lamberty 2018).

1.2.2.3 Uncertainties in decision-making

Decision-makers develop and implement policy in the face of many uncertainties (Rosenzweig and Neofotis 2013; Anav et al. 2013; Ciais et al. 2013a; Stocker et al. 2013b) (Section 7.5). In context of climate change, the term 'deep uncertainty' is frequently used to denote situations in which either the analysis of a situation is inconclusive, or parties to a decision cannot agree on a number of criteria that would help to rank model results in terms of likelihood (e.g., Hallegatte and Mach 2016; Maier et al. 2016) (Sections 7.1 and 7.5, and Table SM.1.2 in Supplementary Material). However, existing uncertainty does not support societal and political inaction.

The many ways of dealing with uncertainty in decision-making can be summarised by two decision approaches: (economic) cost-benefit analysis, and the precautionary approach. A typical variant of cost-benefit analysis is the minimisation of negative consequences. This approach needs reliable probability estimates (Gleckler et al. 2016; Parker 2013) and tends to focus on the short term. The precautionary approach does not take account of probability estimates (cf. Raffensperger and Tickner 1999), but instead focuses on avoiding the worst outcome (Gardiner 2006).

Between these two extremes, various decision approaches seek to address uncertainties in a more reflective manner that avoids the limitations of cost-benefit analysis and the precautionary approach. Climate-informed decision analysis combines various approaches to explore options and the vulnerabilities and sensitivities of certain decisions. Such an approach includes stakeholder involvement (e.g., elicitation methods), and can be combined with, for example, analysis of climate or land-use change modelling (Hallegatte and Rentschler 2015; Luedeling and Shepherd 2016).

Flexibility is facilitated by political decisions that are not set in stone and can change over time (Walker et al. 2013; Hallegatte and Rentschler 2015). Generally, within the research community that investigates deep uncertainty, a paradigm is emerging that requires the development of a strategic vision of the long – or mid-term future, while committing to short-term actions and establishing a framework to guide future actions, including revisions and flexible adjustment of decisions (Haasnoot 2013) (Section 7.5).

1.3 Response options to the key challenges

A number of response options underpin solutions to the challenges arising from GHG emissions from land, and the loss of productivity arising from degradation and desertification. These options are discussed in Sections 2.5 and 6.2 and rely on (i) land management, (ii) value chain management, and (iii) risk management (Table 1.2). None of these response options are mutually exclusive, and it is their combination in a regionally, context-specific manner that is most likely to achieve co-benefits between climate change mitigation, adaptation and other environmental challenges in a cost-effective way (Griscom et al. 2017; Kok et al. 2018). Sustainable solutions affecting both demand and supply are expected to yield most co-benefits if these rely not only on the carbon footprint, but are extended to other vital ecosystems such as water, nutrients and biodiversity footprints (van Noordwijk and Brussaard 2014; Cremasch 2016). As an entry point to the discussion in Chapter 6, we introduce here a selected number of examples that cut across climate change mitigation, food security, desertification, and degradation issues, including potential trade-offs and co-benefits.

Table 1.2 | Broad categorisation of response options into three main classes and eight sub-classes. For illustration, the table includes examples of individual response options. A complete list and description is provided in Chapter 6.

Response options based on land management	
in agriculture	Improved management of: cropland, grazing land, livestock; agro-forestry; avoidance of conversion of grassland to cropland; integrated water management
in forests	Improved management of forests and forest restoration; reduced deforestation and degradation; afforestation
of soils	Increased soil organic carbon content; reduced soil erosion; reduced soil salinisation
across all/other ecosystems	Reduced landslides and natural hazards; reduced pollution including acidification; biodiversity conservation; restoration and reduced conversion of peatlands
specifically for CO_2 removal	Enhanced weathering of minerals; bioenergy and BECCS
Response options based on value chain management	
through demand management	Dietary change; reduced post-harvest losses; reduced food waste
through supply management	Sustainable sourcing; improved energy use in food systems; improved food processing and retailing
Response options based on risk management	
Risk management	Risk-sharing instruments; use of local seeds; disaster risk management

1.3.1 Targeted decarbonisation relying on large land-area need

Most global future scenarios that aim to achieve global warming of 2°C or well below rely on bioenergy (BE; BECCS, with carbon capture and storage; Cross-Chapter Box 7 in Chapter 6) or afforestation and reforestation (de Coninck et al. 2018; Rogelj et al. 2018b,a; Anderson and Peters 2016; Popp et al. 2016; Smith et al. 2016) (Cross-Chapter Box 2 in Chapter 1). In addition to the very large area requirements projected for 2050 or 2100, several other aspects of these scenarios have also been criticised. For instance, they simulate very rapid technological and societal uptake rates for the land-related mitigation measures, when compared with historical observations (Turner et al. 2018; Brown et al. 2019; Vaughan and Gough 2016). Furthermore, *confidence* in the projected bioenergy or BECCS net carbon uptake potential is *low*, because of many diverging assumptions. This includes assumptions about bioenergy crop yields, the possibly large energy demand for CCS, which diminishes the net-GHG-saving of bioenergy systems, or the incomplete accounting for ecosystem processes and of the cumulative carbon-loss arising from natural vegetation clearance for bioenergy crops or bioenergy forests and subsequent harvest regimes (Anderson and Peters 2016; Bentsen 2017; Searchinger et al. 2017; Bayer et al. 2017; Fuchs et al. 2017; Pingoud et al. 2018; Schlesinger 2018). Bioenergy provision under politically unstable conditions may also be a problem (Erb et al. 2012; Searle and Malins 2015).

Large-scale bioenergy plantations and forests may compete for the same land area (Harper et al. 2018). Both potentially have adverse side effects on biodiversity and ecosystem services, as well as socio-economic trade-offs such as higher food prices due to land-area competition (Shi et al. 2013; Bárcena et al. 2014; Fernandez-Martinez et al. 2014; Searchinger et al. 2015; Bonsch et al. 2016; Creutzig et al. 2015; Kreidenweis et al. 2016; Santangeli et al. 2016; Williamson 2016; Graham et al. 2017; Krause et al. 2017; Hasegawa et al. 2018; Humpenoeder et al. 2018). Although forest-based mitigation could have co-benefits for biodiversity and many ecosystem services, this depends on the type of forest planted and the vegetation cover it replaces (Popp et al. 2014; Searchinger et al. 2015) (Cross-Chapter Box 2 in Chapter 1).

There is *high confidence* that scenarios with large land requirements for climate change mitigation may not achieve SDGs, such as no poverty, zero hunger and life on land, if competition for land and the need for agricultural intensification are greatly enhanced (Creutzig et al. 2016; Dooley and Kartha 2018; Hasegawa et al. 2015; Hof et al. 2018; Roy et al. 2018; Santangeli et al. 2016; Boysen et al. 2017; Henry et al. 2018; Kreidenweis et al. 2016; UN 2015). This does not mean that smaller-scale land-based climate mitigation could not have positive outcomes for then achieving these goals (e.g., Sections 6.2, and 4.5, Cross-Chapter Box 7 in Chapter 6).

Cross-Chapter Box 2 | Implications of large-scale conversion from non-forest to forest land

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Efforts to increase forest area

While deforestation continues in many world regions, especially in the tropics, large expansion of mostly managed forest area has taken place in some countries. In the IPCC context, reforestation (conversion to forest of land that previously contained forests but has been converted to some other use) is distinguished from afforestation (conversion to forest of land that historically has not contained forests; see Glossary). Past expansion of managed forest area occurred in many world-regions for a variety of reasons, from meeting needs for wood fuel or timber (Vadell et al. 2016; Joshi et al. 2011; Zaloumis and Bond 2015; Payn et al. 2015; Shoyama 2008; Miyamoto et al. 2011) to restoration-driven efforts, with the aim of enhancing ecological function (Filoso et al. 2017; Salvati and Carlucci 2014; Ogle et al. 2018; Crouzeilles et al. 2016; FAO 2016) (Sections 3.7 and 4.9).

In many regions, net forest area increase includes deforestation (often of native forests) alongside increasing forest area (often managed forest, but also more natural forest restoration efforts) (Heilmayr et al. 2016; Scheidel and Work 2018; Hua et al. 2018; Crouzeilles et al. 2016; Chazdon et al. 2016b). China and India have seen the largest net forest area increase, aiming to alleviate soil erosion, desertification and overgrazing (Ahrends et al. 2017; Cao et al. 2016; Deng et al. 2015; Chen et al. 2019) (Sections 3.7 and 4.9) but uncertainties in exact forest area changes remain large, mostly due to differences in methodology and forest classification (FAO 2015a; Song et al. 2018; Hansen et al. 2013; MacDicken et al. 2015).

What are the implications for ecosystems?

1. Implications for biogeochemical and biophysical processes

There is *robust evidence* and *medium agreement* that whilst forest area expansion increases ecosystem carbon storage, the magnitude of the increased stock depends on the type and length of former land use, forest type planted, and climatic regions (Bárcena et al. 2014; Poeplau et al. 2011; Shi et al. 2013; Li et al. 2012) (Section 4.3). While reforestation of former croplands increases net ecosystem carbon storage (Bernal et al. 2018; Lamb 2018), afforestation on native grassland results in reduction of soil carbon stocks, which can reduce or negate the net carbon benefits which are dominated by increases in biomass, dead wood and litter carbon pools (Veldman et al. 2015, 2017).

Forest vs non-forest lands differ in land surface reflectiveness of shortwave radiation and evapotranspiration (Anderson et al. 2011; Perugini et al. 2017) (Section 2.4). Evapotranspiration from forests during the growing season regionally cools the land surface and enhances cloud cover that reduces shortwave radiation reaching the land, an impact that is especially pronounced in the tropics. However, dark evergreen conifer-dominated forests have low surface reflectance, and tend to cause warming of the near-surface atmosphere compared to non-forest land, especially when snow cover is present such as in boreal regions (Duveiller et al. 2018; Alkama and Cescatti 2016; Perugini et al. 2017) (*medium evidence, high agreement*).

2. Implications for water balance

Evapotranspiration by forests reduces surface runoff and erosion of soil and nutrients (Salvati et al. 2014). Planting of fast-growing species in semi-arid regions or replacing natural grasslands with forest plantations can divert soil water resources to evapotranspiration from groundwater recharge (Silveira et al. 2016; Zheng et al. 2016; Cao et al. 2016). Multiple cases are reported from China where afforestation programs, some with irrigation, without having been tailored to local precipitation conditions, resulted in water shortages and tree mortality (Cao et al. 2016; Yang et al. 2014; Li et al. 2014; Feng et al. 2016). Water shortages may create long-term water conflicts (Zheng et al. 2016). However, reforestation (in particular for restoration) is also associated with improved water filtration, groundwater recharge (Ellison et al. 2017) and can reduce risk of soil erosion, flooding, and associated disasters (Lee et al. 2018) (Section 4.9).

3. Implications for biodiversity

Impacts of forest area expansion on biodiversity depend mostly on the vegetation cover that is replaced: afforestation on natural non-tree-dominated ecosystems can have negative impacts on biodiversity (Abreu et al. 2017; Griffith et al. 2017; Veldman et al. 2015; Parr et al. 2014; Wilson et al. 2017; Hua et al. 2016; see also IPCC 1.5° report (2018)). Reforestation with monocultures of fast-growing, non-native trees has little benefit to biodiversity (Shimamoto et al. 2018; Hua et al. 2016). There are also concerns regarding some commonly used plantation species (e.g., Acacia and Pinus species) to become invasive (Padmanaba and Corlett 2014; Cunningham et al. 2015b).

Cross-Chapter Box 2 (continued)

Reforestation with mixes of native species, especially in areas that retain fragments of native forest, can support ecosystem services and biodiversity recovery, with positive social and environmental co-benefits (Cunningham et al. 2015a; Dendy et al. 2015; Chaudhary and Kastner 2016; Huang et al. 2018; Locatelli et al. 2015b) (Section 4.5). Even though species diversity in re-growing forests is typically lower than in primary forests, planting native or mixed species can have positive effects on biodiversity (Brockerhoff et al. 2013; Pawson et al. 2013; Thompson et al. 2014). Reforestation has been shown to improve links among existing remnant forest patches, increasing species movement, and fostering gene flow between otherwise isolated populations (Gilbert-Norton et al. 2010; Barlow et al. 2007; Lindenmayer and Hobbs 2004).

4. Implications for other ecosystem services and societies

Forest area expansion could benefit recreation and health, preservation of cultural heritage and local values and knowledge, livelihood support (via reduced resource conflicts, restoration of local resources). These social benefits could be most successfully achieved if local communities' concerns are considered (Le et al. 2012). However, these co-benefits have rarely been assessed due to a lack of suitable frameworks and evaluation tools (Baral et al. 2016).

Industrial forest management can be in conflict with the needs of forest-dependent people and community-based forest management over access to natural resources (Gerber 2011; Baral et al. 2016) and/or loss of customary rights over land use (Malkamäki et al. 2018; Cotula et al. 2014). A common result is out-migration from rural areas and diminishing local uses of ecosystems (Gerber 2011). Policies promoting large-scale tree plantations gain traction if these are reappraised in view of potential co-benefits with several ecosystem services and local societies (Bull et al. 2006; Le et al. 2012).

Scenarios of forest area expansion for land-based climate change mitigation

Conversion of non-forest to forest land has been discussed as a relatively cost-effective climate change mitigation option when compared to options in the energy and transport sectors (*medium evidence, medium agreement*) (de Coninck et al. 2018; Griscom et al. 2017; Fuss et al. 2018), and can have co-benefits with adaptation.

Sequestration of CO_2 from the atmosphere through forest area expansion has become a fundamental part of stringent climate change mitigation scenarios (Rogelj et al. 2018a; Fuss et al. 2018) (e.g., Sections 2.5, 4.5 and 6.2). The estimated mitigation potential ranges from about 0.5 to 10 $GtCO_2$ yr^{-1} (*robust evidence, medium agreement*), and depends on assumptions regarding available land and forest carbon uptake potential (Houghton 2013; Houghton and Nassikas 2017; Griscom et al. 2017; Lenton 2014; Fuss et al. 2018; Smith 2016) (Section 2.5.1). In climate change mitigation scenarios, typically, no differentiation is made between reforestation and afforestation despite different overall environmental impacts between these two measures. Likewise, biodiversity conservation, impacts on water balances, other ecosystem services, or land-ownership – as constraints when simulating forest area expansion (Cross-Chapter Box 1 in Chapter 1) – tend not to be included as constraints when simulating forest area expansion.

Projected forest area increases, relative to today's forest area, range from approximately 25% in 2050 and increase to nearly 50% by 2100 (Rogelj et al. 2018a; Kreidenweis et al. 2016; Humpenoder et al. 2014). Potential adverse side-effects of such large-scale measures, especially for low-income countries, could be increasing food prices from the increased competition for land (Kreidenweis et al. 2016; Hasegawa et al. 2015, 2018; Boysen et al. 2017) (Section 5.5). Forests also emit large amounts of biogenic volatile compounds that under some conditions contribute to the formation of atmospherically short-lived climate forcing compounds, which are also detrimental to health (Ashworth et al. 2013; Harrison et al. 2013). Recent analyses argued for an upper limit of about 5 million km^2 of land globally available for climate change mitigation through reforestation, mostly in the tropics (Houghton 2013) – with potential regional co-benefits.

Since forest growth competes for land with bioenergy crops (Harper et al. 2018) (Cross-Chapter Box 7 in Chapter 6), global area estimates need to be assessed in light of alternative mitigation measures at a given location. In all forest-based mitigation efforts, the sequestration potential will eventually saturate unless the area keeps expanding, or harvested wood is either used for long-term storage products or for carbon capture and storage (Fuss et al. 2018; Houghton et al. 2015) (Section 2.5.1). Considerable uncertainty in forest carbon uptake estimates is further introduced by potential forest losses from fire or pest outbreaks (Allen et al. 2010; Anderegg et al. 2015) (Cross-Chapter Box 3 in Chapter 2). And like all land-based mitigation measures, benefits may be diminshed by land-use displacement, and through trade of land-based products, especially in poor countries that experience forest loss (e.g., Africa) (Bhojvaid et al. 2016; Jadin et al. 2016).

Cross-Chapter Box 2 (continued)

Conclusion

Reforestation is a mitigation measure with potential co-benefits for conservation and adaptation, including biodiversity habitat, air and water filtration, flood control, enhanced soil fertility and reversal of land degradation. Potential adverse side-effects of forest area expansion depend largely on the state of the land it displaces as well as tree species selections. Active governance and planning contribute to maximising co-benefits while minimising adverse side-effects (Laestadius et al. 2011; Dinerstein et al. 2015; Veldman et al. 2017) (Section 4.8 and Chapter 7). At large spatial scales, forest expansion is expected to lead to increased competition for land, with potentially undesirable impacts on food prices, biodiversity, non-forest ecosystems and water availability (Bryan and Crossman 2013; Boysen et al. 2017; Kreidenweis et al. 2016; Egginton et al. 2014; Cao et al. 2016; Locatelli et al. 2015a; Smith et al. 2013).

1.3.2 Land management

1.3.2.1 Agricultural, forest and soil management

Sustainable land management (SLM) describes "the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs while simultaneously assuring the long-term productive potential of these resources and the maintenance of their environmental functions" (Alemu 2016; Altieri and Nicholls 2017) (e.g., Section 4.1.5), and includes ecological, technological and governance aspects.

The choice of SLM strategy is a function of regional context and land-use types, with *high agreement* on (a combination of) choices such as agroecology (including agroforestry), conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the preservation and protection of pollination services, rainwater harvesting, range and pasture management, and precision agriculture systems (Stockmann et al. 2013; Ebert, 2014; Schulte et al. 2014; Zhang et al. 2015; Sunil and Pandravada 2015; Poeplau and Don 2015; Agus et al. 2015; Keenan 2015; MacDicken et al. 2015; Abberton et al. 2016). Conservation agriculture and forestry uses management practices with minimal soil disturbance such as no tillage or minimum tillage, permanent soil cover with mulch, combined with rotations to ensure a permanent soil surface, or rapid regeneration of forest following harvest (Hobbs et al. 2008; Friedrich et al. 2012). Vegetation and soils in forests and woodland ecosystems play a crucial role in regulating critical ecosystem processes, therefore reduced deforestation together with sustainable forest management are integral to SLM (FAO 2015b) (Section 4.8). In some circumstances, increased demand for forest products can also lead to increased management of carbon storage in forests (Favero and Mendelsohn 2014). Precision agriculture is characterised by a "management system that is information and technology based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield, for optimum profitability, sustainability, and protection of the environment" (USDA 2007) (Cross-Chapter Box 6 in Chapter 5). The management of protected areas that reduce deforestation also plays an important role in climate change mitigation and adaptation while delivering numerous ecosystem services and sustainable development benefits (Bebber and Butt 2017). Similarly, when managed in an integrated and sustainable way, peatlands are also known to provide numerous ecosystem services, as well as socio-economic and mitigation and adaptation benefits (Ziadat et al. 2018).

Biochar is an organic compound used as soil amendment and is believed to be potentially an important global resource for mitigation. Enhancing the carbon content of soil and/or use of biochar (Chapter 4) have become increasingly important as a climate change mitigation option with possibly large co-benefits for other ecosystem services. Enhancing soil carbon storage and the addition of biochar can be practiced with limited competition for land, provided no productivity/yield loss and abundant unused biomass, but evidence is limited and impacts of large scale application of biochar on the full GHG balance of soils, or human health are yet to be explored (Gurwick et al. 2013; Lorenz and Lal 2014; Smith 2016).

1.3.3 Value chain management

1.3.3.1 Supply management

Food losses from harvest to retailer. Approximately one-third of losses and waste in the food system occurs between crop production and food consumption, increasing substantially if losses in livestock production and overeating are included (Gustavsson et al. 2011; Alexander et al. 2017). This includes on-farm losses, farm to retailer losses, as well retailer and consumer losses (Section 1.3.3.2).

Post-harvest food loss – on farm and from farm to retailer – is a widespread problem, especially in developing countries (Xue et al. 2017), but are challenging to quantify. For instance, averaged for eastern and southern Africa an estimated 10–17% of annual grain production is lost (Zorya et al. 2011). Across 84 countries and different time periods, annual median losses in the supply chain before retailing were estimated at about 28 kg per capita for cereals or about 12 kg per capita for eggs and dairy products (Xue et al. 2017). For the year 2013, losses prior to the reaching retailers were estimated at 20% (dry weight) of the production amount (22% wet weight) (Gustavsson et al. 2011; Alexander et al. 2017). While losses of food cannot be realistically reduced to zero, advancing harvesting technologies (Bradford et al. 2018; Affognon et al. 2015), storage capacity (Chegere 2018) and efficient transportation could all contribute to reducing these losses with co-benefits for food availability, the land area needed for food production and related GHG emissions.

Stability of food supply, transport and distribution. Increased climate variability enhances fluctuations in world food supply and price variability (Warren 2014; Challinor et al. 2015; Elbehri et al. 2017). 'Food price shocks' need to be understood regarding their transmission across sectors and borders and impacts on poor and food insecure populations, including urban poor subject to food deserts and inadequate food accessibility (Widener et al. 2017; Lehmann et al. 2013; Le 2016; FAO 2015b). Trade can play an important stabilising role in food supply, especially for regions with agro-ecological limits to production, including water scarce regions, as well as regions that experience short-term production variability due to climate, conflicts or other economic shocks (Gilmont 2015; Marchand et al. 2016). Food trade can either increase or reduce the overall environmental impacts of agriculture (Kastner et al. 2014). Embedded in trade are virtual transfers of water, land area, productivity, ecosystem services, biodiversity, or nutrients (Marques et al. 2019; Wiedmann and Lenzen 2018; Chaudhary and Kastner 2016) with either positive or negative implications (Chen et al. 2018; Yu et al. 2013). Detrimental consequences in countries in which trade dependency may accentuate the risk of food shortages from foreign production shocks could be reduced by increasing domestic reserves or importing food from a diversity of suppliers (Gilmont 2015; Marchand et al. 2016).

Climate mitigation policies could create new trade opportunities (e.g., biomass) (Favero and Massetti 2014) or alter existing trade patterns. The transportation GHG footprints of supply chains may be causing a differentiation between short and long supply chains (Schmidt et al. 2017) that may be influenced by both economics and policy measures (Section 5.4). In the absence of sustainable practices and when the ecological footprint is not valued through the market system, trade can also exacerbate resource exploitation and environmental leakages, thus weakening trade mitigation contributions (Dalin and Rodríguez-Iturbe 2016; Mosnier et al. 2014; Elbehri et al. 2017). Ensuring stable food supply while pursuing climate mitigation and adaptation will benefit from evolving trade rules and policies that allow internalisation of the cost of carbon (and costs of other vital resources such as water, nutrients). Likewise, future climate change mitigation policies would gain from measures designed to internalise the environmental costs of resources and the benefits of ecosystem services (Elbehri et al. 2017; Brown et al. 2007).

1.3.3.2 Demand management

Dietary change. Demand-side solutions to climate mitigation are an essential complement to supply-side, technology and productivity driven solutions (*high confidence*) (Creutzig et al. 2016; Bajželj et al. 2014; Erb et al. 2016b; Creutzig et al. 2018) (Sections 5.5.1 and 5.5.2). The environmental impacts of the animal-rich 'western diets' are being examined critically in the scientific literature (Hallström et al. 2015; Alexander et al. 2016b; Alexander et al. 2015; Tilman and Clark 2014; Aleksandrowicz et al. 2016; Poore and Nemecek 2018) (Section 5.4.6). For example, if the average diet of each country were consumed globally, the agricultural land area needed to supply these diets would vary 14-fold, due to country differences in ruminant protein and calorific intake (–55% to +178% compared to existing cropland areas). Given the important role enteric fermentation plays in methane (CH_4) emissions, a number of studies have examined the implications of lower animal-protein diets (Swain et al. 2018; Röös et al. 2017; Rao et al. 2018). Reduction of animal protein intake has been estimated to reduce global green water (from precipitation) use by 11% and blue water (from rivers, lakes, groundwater) use by 6% (Jalava et al. 2014). By avoiding meat from producers with above-median GHG emissions and halving animal-product intake, consumption change could free-up 21 million km^2 of agricultural land and reduce GHG emissions by nearly 5 $GtCO_2$-eq yr^{-1} or up to 10.4 $GtCO_2$-eq yr^{-1} when vegetation carbon uptake is considered on the previously agricultural land (Poore and Nemecek 2018, 2019).

Diets can be location and community specific, are rooted in culture and traditions while responding to changing lifestyles driven for instance by urbanisation and changing income. Changing dietary and consumption habits would require a combination of non-price (government procurement, regulations, education and awareness raising) and price incentives (Juhl and Jensen 2014) to induce consumer behavioural change with potential synergies between climate, health and equity (addressing growing global nutrition imbalances that emerge as undernutrition, malnutrition, and obesity) (FAO 2018b).

Reduced waste and losses in the food demand system. Global averaged per capita food waste and loss (FWL) have increased by 44% between 1961 and 2011 (Porter et al. 2016) and are now around 25–30% of global food produced (Kummu et al. 2012; Alexander et al. 2017). Food waste occurs at all stages of the food supply chain from the household to the marketplace (Parfitt et al. 2010) and is found to be larger at household than at supply chain levels. A meta-analysis of 55 studies showed that the highest share of food waste was at the consumer stage (43.9% of total) with waste increasing with per capita GDP for high-income countries until a plateaux at about 100 kg cap^{-1} yr^{-1} (around 16% of food consumption) above about 70,000 USD cap^{-1} (van der Werf and Gilliland 2017; Xue et al. 2017). Food loss from supply chains tends to be more prevalent in less developed countries where inadequate technologies, limited infrastructure, and imperfect markets combine to raise the share of the food production lost before use.

There are several causes behind food waste including economics (cheap food), food policies (subsidies) as well as individual behaviour (Schanes et al. 2018). Household level food waste arises from overeating or overbuying (Thyberg and Tonjes 2016). Globally, overconsumption was found to waste 9–10% of food bought (Alexander et al. 2017).

Solutions to FWL thus need to address technical and economic aspects. Such solutions would benefit from more accurate data on the loss-source, loss-magnitude and causes along the food supply chain. In the long run, internalising the cost of food waste into the product price would more likely induce a shift in consumer behaviour towards less waste and more nutritious, or alternative, food intake (FAO 2018b). Reducing FWL would bring a range of benefits for health, reducing pressures on land, water and nutrients, lowering emissions and safeguarding food security. Reducing food waste by 50% would generate net emissions reductions in the range of 20 to 30% of total food-sourced GHGs (Bajželj et al. 2014). SDG 12 ("Ensure sustainable consumption and production patterns") calls for per capita global food waste to be reduced by one-half at the retail and consumer level, and reducing food losses along production and supply chains by 2030.

1.3.4 Risk management

Risk management refers to plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks. Insurance and early warning systems are examples of risk management, but risk can also be reduced (or resilience enhanced) through a broad set of options ranging from seed sovereignty, livelihood diversification, to reducing land loss through urban sprawl. Early warning systems support farmer decision-making on management strategies (Section 1.2) and are a good example of an adaptation measure with mitigation co-benefits such as reducing carbon losses (Section 1.3.6). Primarily designed to avoid yield losses, early warning systems also support fire management strategies in forest ecosystems, which prevents financial as well as carbon losses (de Groot et al. 2015). Given that over recent decades on average around 10% of cereal production was lost through extreme weather events (Lesk et al. 2016), where available and affordable, insurance can buffer farmers and foresters against the financial losses incurred through such weather and other (fire, pests) extremes (Falco et al. 2014) (Sections 7.2 and 7.4). Decisions to take up insurance are influenced by a range of factors such as the removal of subsidies or targeted education (Falco et al. 2014). Enhancing access and affordability of insurance in low-income countries is a specific objective of the UNFCCC (Linnerooth-Bayer and Mechler 2006). A global mitigation co-benefit of insurance schemes may also include incentives for future risk reduction (Surminski and Oramas-Dorta 2014).

1.3.5 Economics of land-based mitigation pathways: Costs versus benefits of early action under uncertainty

The overarching societal costs associated with GHG emissions and the potential implications of mitigation activities can be measured by various metrics (cost-benefit analysis, cost effectiveness analysis) at different scales (project, technology, sector or the economy) (IPCC 2018) (Section 1.4). The social cost of carbon (SCC) measures the total net damages of an extra metric tonne of CO_2 emissions due to the associated climate change (Nordhaus 2014; Pizer et al. 2014). Both negative and positive impacts are monetised and discounted to arrive at the net value of consumption loss. As the SCC depends on discount rate assumptions and value judgements (e.g., relative weight given to current vs future generations), it is not a straightforward policy tool to compare alternative options. At the sectoral level, marginal abatement cost curves (MACCs) are widely used for the assessment of costs related to GHG emissions reduction. MACCs measure the cost of reducing one more GHG unit and are either expert-based or model-derived and offer a range of approaches and assumptions on discount rates or available abatement technologies (Kesicki 2013). In land-based sectors, Gillingham and Stock (2018) reported short-term static abatement costs for afforestation of between 1 and 10 USD2017 per tCO_2, soil management at 57 and livestock management at 71 USD2017 per tCO_2. MACCs are more reliable when used to rank alternative options compared to a baseline (or business as usual) rather than offering absolute numerical measures (Huang et al. 2016). The economics of land-based mitigation options encompass also the "costs of inaction" that arise either from the economic damages due to continued accumulation of GHGs in the atmosphere and from the diminution in value of ecosystem services or the cost of their restoration where feasible (Rodriguez-Labajos 2013; Ricke et al. 2018). Overall, it remains challenging to estimate the costs of alternative mitigation options owing to the context – and scale-specific interplay between multiple drivers (technological, economic, and socio-cultural) and enabling policies and institutions (IPCC 2018) (Section 1.4).

The costs associated with mitigation (both project-linked such as capital costs or land rental rates, or sometimes social costs) generally increase with stringent mitigation targets and over time. Sources of uncertainty include the future availability, cost and performance of technologies (Rosen and Guenther 2015; Chen et al. 2016) or lags in decision-making, which have been demonstrated by the uptake of land use and land utilisation policies (Alexander et al. 2013; Hull et al. 2015; Brown et al. 2018b). There is growing evidence of significant mitigation gains through conservation, restoration and improved land management practices (Griscom et al. 2017; Kindermann et al. 2008; Golub et al. 2013; Favero et al. 2017) (Chapters 4 and 6), but the mitigation cost efficiency can vary according to region and specific ecosystem (Albanito et al. 2016). Recent model developments that treat process-based, human–environment interactions have recognised feedbacks that reinforce or dampen the original stimulus for land-use change (Robinson et al. 2017; Walters and Scholes 2017). For instance, land mitigation interventions that rely on large-scale, land-use change (e.g., afforestation) would need to account for the rebound effect (which dampens initial impacts due to feedbacks) in which raising land prices also raises the cost of land-based mitigation (Vivanco et al. 2016). Although there are few direct estimates, indirect assessments strongly point to much higher costs if action is delayed or limited in scope (*medium confidence*). Quicker response options are also needed to avoid loss of high-carbon ecosystems and other vital ecosystem services that provide multiple services that are difficult to replace (peatlands, wetlands, mangroves, forests) (Yirdaw et al. 2017; Pedrozo-Acuña et al. 2015). Delayed action would raise relative costs in the future or could make response options less feasible (*medium confidence*) (Goldstein et al. 2019; Butler et al. 2014).

1.3.6 Adaptation measures and scope for co-benefits with mitigation

Adaptation and mitigation have generally been treated as two separate discourses, both in policy and practice, with mitigation addressing cause and adaptation dealing with the consequences of climate change (Hennessey et al. 2017). While adaptation (e.g., reducing flood risks) and mitigation (e.g., reducing non-CO_2 emissions from agriculture) may have different objectives and operate at different scales, they can also generate joint outcomes (Locatelli et al. 2015b) with adaptation generating mitigation co-benefits. Seeking to integrate strategies for achieving adaptation and mitigation goals is attractive in order to reduce competition for limited resources and trade-offs (Lobell et al. 2013; Berry et al. 2015; Kongsager and Corbera 2015). Moreover, determinants that can foster adaptation and mitigation practices are similar. These tend to include available technology and resources, and credible information for policymakers to act on (Yohe 2001).

Four sets of mitigation–adaptation interrelationships can be distinguished: (i) mitigation actions that can result in adaptation benefits; (ii) adaptation actions that have mitigation benefits; (iii) processes that have implications for both adaptation and mitigation; and (iv) strategies and policy processes that seek to promote an integrated set of responses for both adaptation and mitigation (Klein et al. 2007). A high level of adaptive capacity is a key ingredient to developing successful mitigation policy. Implementing mitigation action can result in increasing resilience especially if it is able to reduce risks. Yet, mitigation and adaptation objectives, scale of implementation, sector and even metrics to identify impacts tend to differ (Ayers and Huq 2009), and institutional setting, often does not enable an environment where synergies are sought (Kongsager et al. 2016). Trade-offs between adaptation and mitigation exist as well and need to be understood (and avoided) to establish win-win situations (Porter et al. 2014; Kongsager et al. 2016).

Forestry and agriculture offer a wide range of lessons for the integration of adaptation and mitigation actions given the vulnerability of forest ecosystems or cropland to climate variability and change (Keenan 2015; Gaba et al. 2015) (Sections 5.6 and 4.8). Increasing adaptive capacity in forested areas has the potential to prevent deforestation and forest degradation (Locatelli et al. 2011). Reforestation projects, if well managed, can increase community economic opportunities that encourage conservation (Nelson and de Jong 2003), build capacity through training of farmers and installation of multifunctional plantations with income generation (Reyer et al. 2009), strengthen local institutions (Locatelli et al. 2015a) and increase cash-flow to local forest stakeholders from foreign donors (West 2016). A forest plantation that sequesters carbon for mitigation can also reduce water availability to downstream populations and heighten their vulnerability to drought. Inversely, not recognising mitigation in adaptation projects may yield adaptation measures that increase greenhouse gas emissions, a prime example of 'maladaptation'. Analogously, 'mal-mitigation' would result in reducing GHG emissions, but increasing vulnerability (Barnett and O'Neill 2010; Porter et al. 2014). For instance, the cost of pursuing large-scale adaptation and mitigation projects has been associated with higher failure risks, onerous transactions costs and the complexity of managing big projects (Swart and Raes 2007).

Adaptation encompasses both biophysical and socio-economic vulnerability and underlying causes (informational, capacity, financial, institutional, and technological; Huq et al. 2014) and it is increasingly linked to resilience and to broader development goals (Huq et al. 2014). Adaptation measures can increase performance of mitigation projects under climate change and legitimise mitigation measures through the more immediately felt effects of adaptation (Locatelli et al. 2011; Campbell et al. 2014; Locatelli et al. 2015b). Effective climate policy integration in the land sector is expected to gain from (i) internal policy coherence between adaptation and mitigation objectives, (ii) external climate coherence between climate change and development objectives, (iii) policy integration that favours vertical governance structures to foster effective mainstreaming of climate change into sectoral policies, and (iv) horizontal policy integration through overarching governance structures to enable cross-sectoral coordination (Sections 1.4 and 7.4).

1.4 Enabling the response

Climate change and sustainable development are challenges to society that require action at local, national, transboundary and global scales. Different time-perspectives are also important in decision-making, ranging from immediate actions to long-term planning and investment. Acknowledging the systemic link between food production and consumption, and land-resources more broadly is expected to enhance the success of actions (Bazilian et al. 2011; Hussey and Pittock 2012). Because of the complexity of challenges and the diversity of actors involved in addressing these challenges, decision-making would benefit from a portfolio of policy instruments. Decision-making would also be facilitated by overcoming barriers such as inadequate education and funding mechanisms, as well as integrating international decisions into all relevant (sub)national sectoral policies (Section 7.4).

'Nexus thinking' emerged as an alternative to the sector-specific governance of natural resource use to achieve global securities of water (D'Odorico et al. 2018), food and energy (Hoff 2011; Allan et al. 2015), and also to address biodiversity concerns (Fischer et al. 2017). Yet, there is no agreed definition of "nexus" nor a uniform framework to approach the concept, which may be land-focused (Howells et al. 2013), water-focused (Hoff 2011) or food-centred (Ringler and Lawford 2013; Biggs et al. 2015). Significant barriers remain to establish nexus approaches as part of a wider repertoire of responses to global environmental change, including challenges to cross-disciplinary collaboration, complexity, political economy and the incompatibility of current institutional structures (Hayley et al. 2015; Wichelns 2017) (Sections 7.5.6 and 7.6.2).

1.4.1 Governance to enable the response

Governance includes the processes, structures, rules and traditions applied by formal and informal actors including governments, markets, organisations, and their interactions with people. Land governance actors include those affecting policies and markets, and those directly changing land use (Hersperger et al. 2010). The former includes governments and administrative entities, large companies investing in land, non-governmental institutions and international institutions. It also includes UN agencies that are working at the interface between climate change and land management, such as the FAO and the World Food Programme that have *inter alia* worked on advancing knowledge to support food security through the improvement of techniques and strategies for more resilient farm systems. Farmers and foresters directly act on land (actors in proximate causes) (Hersperger et al. 2010) (Chapter 7).

Policy design and formulation has often been strongly sectoral. For example, agricultural policy might be concerned with food security, but have little concern for environmental protection or human health. As food, energy and water security and the conservation of biodiversity rank highly on the Agenda 2030 for Sustainable Development, the promotion of synergies between and across sectoral policies is important (IPBES 2018a). This can also reduce the risks of anthropogenic climate forcing through mitigation, and bring greater collaboration between scientists, policymakers, the private sector and land managers in adapting to climate change (FAO 2015a). Polycentric governance (Section 7.6) has emerged as an appropriate way of handling resource management problems, in which the decision-making centres take account of one another in competitive and cooperative relationships and have recourse to conflict resolution mechanisms (Carlisle and Gruby 2017). Polycentric governance is also multi-scale and allows the interaction between actors at different levels (local, regional, national and global) in managing common pool resources such as forests or aquifers.

Implementation of systemic, nexus approaches has been achieved through socio-ecological systems (SES) frameworks that emerged from studies of how institutions affect human incentives, actions and outcomes (Ostrom and Cox 2010). Recognition of the importance of SES laid the basis for alternative formulations to tackle the sustainable management of land resources focusing specifically on institutional and governance outcomes (Lebel et al. 2006; Bodin 2017). The SES approach also addresses the multiple scales in which the social and ecological dimensions interact (Veldkamp et al. 2011; Myers et al. 2016; Azizi et al. 2017) (Section 6.1).

Adaptation or resilience pathways within the SES frameworks require several attributes, including indigenous and local knowledge (ILK) and trust building for deliberative decision-making and effective collective action, polycentric and multi-layered institutions and responsible authorities that pursue just distributions of benefits to enhance the adaptive capacity of vulnerable groups and communities (Lebel et al. 2006). 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; Schneider and Buser 2018). Integrating ILK with scientific information is a prerequisite for such community-owned solutions (Cross-Chapter Box 13 in Chapter 7). ILK is context-specific, transmitted orally or through imitation and demonstration, adaptive to changing environments, and collectivised through a shared social memory (Mistry and Berardi 2016). ILK is also holistic since indigenous people do not seek solutions aimed at adapting to climate change alone, but instead look for solutions to increase their resilience to a wide range of shocks and stresses (Mistry and Berardi 2016). 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). ILK need not be viewed as needing confirmation or disapproval by formal science, but rather it can complement scientific knowledge (Klein et al. 2014).

The capacity to apply individual policy instruments and policy mixes is influenced by governance modes. These modes include hierarchical governance that is centralised and imposes policy through top-down measures, decentralised governance in which public policy is devolved to regional or local government, public-private partnerships that aim for mutual benefits for the public and private sectors and self or private governance that involves decisions beyond the realms of the public sector (IPBES 2018a). These governance modes provide both constraints and opportunities for key actors that impact the effectiveness, efficiency and equity of policy implementation.

1.4.2 Gender agency as a critical factor in climate and land sustainability outcomes

Environmental resource management is not gender neutral. Gender is an essential variable in shaping ecological processes and change, building better prospects for livelihoods and sustainable development (Resurrección 2013) (Cross-Chapter Box 11 in Chapter 7). Entrenched legal and social structures and power relations constitute additional stressors that render women's experience of natural resources disproportionately negative when compared to men. Socio-economic drivers and entrenched gender inequalities affect land-based management (Agarwal 2010). The intersections between climate change, gender and climate adaptation takes place at multiple scales: household, national and international, and adaptive capacities are shaped through power and knowledge.

Germaine to the gender inequities is the unequal access to land-based resources. Women play a significant role in agriculture (Boserup 1989; Darity 1980) and rural economies globally (FAO 2011), but are well below their share of labour in agriculture globally (FAO 2011). In 59% of 161 surveyed countries, customary, traditional and religious practices hinder women's land rights (OECD 2014). Moreover, women typically shoulder disproportionate responsibility for unpaid domestic work including care-giving activities (Beuchelt and Badstue 2013) and the provision of water and firewood (UNEP 2016). Exposure to violence restricts, in large regions, their mobility for capacity-building activities and productive work outside the home (Day et al. 2005; UNEP 2016). Large-scale development projects can erode rights, and lead to over-exploitation of natural resources. Hence, there are cases where reforms related to land-based management, instead of enhancing food security, have tended to increase the vulnerability of both women and men and reduce their ability to adapt to climate change (Pham et al. 2016). Access to, and control over, land and land-based resources is essential in taking concrete action on land-based mitigation, and inadequate access can affect women's rights and participation in land governance and management of productive assets.

Timely information, such as from early warning systems, is critical in managing risks, disasters, and land degradation, and in enabling land-based adaptation. Gender, household resources and social status, are all determinants that influence the adoption of land-based strategies (Theriault et al. 2017). Climate change is not a lone driver in the marginalisation of women; their ability to respond swiftly to its impacts will depend on other socio-economic drivers that may help or hinder action towards adaptive governance. Empowering women and removing gender-based inequities constitutes a mechanism for greater participation in the adoption of sustainable practices of land management (Mello and Schmink 2017). Improving women's access to land (Arora-Jonsson 2014) and other resources (water) and means of economic livelihoods (such as credit and finance) are the prerequisites to enable women to participate in governance and decision-making structures (Namubiru-Mwaura 2014). Still, women are not a homogenous group, and distinctions through elements of ethnicity, class, age and social status, require a more nuanced approach and not a uniform treatment through vulnerability lenses only. An intersectional approach that accounts for various social identifiers under different situations of power (Rao 2017) is considered suitable to integrate gender into climate change research and helps to recognise overlapping and interdependent systems of power (Djoudi et al. 2016; Kaijser and Kronsell 2014; Moosa and Tuana 2014; Thompson-Hall et al. 2016).

1.4.3 Policy instruments

Policy instruments enable governance actors to respond to environmental and societal challenges through policy action. Examples of the range of policy instruments available to public policymakers are discussed below based on four categories of instruments: (i) legal and regulatory instruments, (ii) rights-based instruments and customary norms, (iii) economic and financial instruments, and (iv) social and cultural instruments.

1.4.3.1 Legal and regulatory instruments

Legal and regulatory instruments deal with all aspects of intervention by public policy organisations to correct market failures, expand market reach, or intervene in socially relevant areas with inexistent markets. Such instruments can include legislation to limit the impacts of intensive land management, for example, protecting areas that are susceptible to nitrate pollution or soil erosion. Such instruments can also set standards or threshold values, for example, mandated water quality limits, organic production standards, or geographically defined regional food products. Legal and regulatory instruments may also define liability rules, for example, where environmental standards are not met, as well as establishing long-term agreements for land resource protection with land owners and land users.

1.4.3.2 Economic and financial instruments

Economic (such as taxes, subsidies) and financial (weather-index insurance) instruments deal with the many ways in which public policy organisations can intervene in markets. A number of instruments are available to support climate mitigation actions including public provision, environmental regulations, creating property rights and markets (Sterner 2003). Market-based policies such as carbon taxes, fuel taxes, cap and trade systems or green payments have been promoted (mostly in industrial economies) to encourage markets and businesses to contribute to climate mitigation, but their effectiveness to date has not always matched expectations (Grolleau et al. 2016) (Section 7.4.4). Market-based instruments in ecosystem services generate both positive (incentives for conservation), but also negative environmental impacts, and also push food prices up or increase price instability (Gómez-Baggethun and Muradian 2015; Farley and Voinov 2016). Footprint labels can be an effective means of shifting consumer behaviour. However, private labels focusing on a single metric (e.g., carbon) may give misleading signals if they target a portion of the life cycle (e.g., transport) (Appleton 2009) or ignore other ecological indicators (water, nutrients, biodiversity) (van Noordwijk and Brussaard 2014).

Effective and durable, market-led responses for climate mitigation depend on business models that internalise the cost of emissions into economic calculations. Such 'business transformation' would itself require integrated policies and strategies that aim to account for emissions in economic activities (Biagini and Miller 2013; Weitzman 2014; Eidelwein et al. 2018). International initiatives such as REDD+ and agricultural commodity roundtables (beef, soybeans, palm oil, sugar) are expanding the scope of private sector participation in climate mitigation (Nepstad et al. 2013), but their impacts have not always been effective (Denis et al. 2014). Payments for environmental services (PES) defined as "voluntary transactions between service users and service providers that are conditional on agreed rules of natural resource management for generating offsite services" (Wunder 2015) have not been widely adopted and have not yet been demonstrated to deliver as effectively as originally hoped (Börner et al. 2017) (Sections 7.4 and 7.5). PES in forestry were shown to be effective only when coupled with appropriate regulatory measures (Alix-Garcia and Wolff 2014). Better designed and expanded PES schemes would encourage integrated soil–water–nutrient management packages (Stavi et al. 2016), services for pollinator protection (Nicole 2015), water use governance under scarcity, and engage both public and private actors (Loch et al. 2013). Effective PES also requires better economic metrics to account for human-directed losses in terrestrial ecosystems and to food potential, and to address market failures or externalities unaccounted for in market valuation of ecosystem services.

Resilient strategies for climate adaptation can rely on the construction of markets through social networks as in the case of livestock systems (Denis et al. 2014) or when market signals encourage adaptation through land markets or supply chain incentives for sustainable land management practices (Anderson et al. 2018). Adequate policy (through regulations, investments in research and development or support to social capabilities) can support private initiatives for effective solutions to restore degraded lands (Reed and Stringer 2015), or mitigate against risk and to avoid shifting risks to the public (Biagini and Miller 2013). Governments, private business, and community groups could also partner to develop sustainable production codes (Chartres and Noble 2015), and in co-managing land-based resources (Baker and Chapin 2018), while public-private partnerships can be effective mechanisms in deploying infrastructure to cope with climatic events (floods) and for climate-indexed insurance (Kunreuther 2015). Private initiatives that depend on trade for climate adaptation and mitigation require reliable trading systems that do not impede climate mitigation objectives (Elbehri et al. 2015; Mathews 2017).

1.4.3.3 Rights-based instruments and customary norms

Rights-based instruments and customary norms deal with the equitable and fair management of land resources for all people (IPBES 2018a). These instruments emphasise the rights in particular of indigenous peoples and local communities, including for example, recognition of the rights embedded in the access to, and use of, common land. Common land includes situations without legal ownership (e.g., hunter-gathering communities in South America or Africa, and bushmeat), where the legal ownership is distinct from usage rights (Mediterranean transhumance grazing systems), or mixed ownership-common grazing systems (e.g., crofting in Scotland). A lack of formal (legal) ownership has often led to the loss of access rights to land, where these rights were also not formally enshrined in law, which especially effects indigenous communities, for example, deforestation in the Amazon basin. Overcoming the constraints associated with common-pool resources (forestry, fisheries, water) are often of economic and institutional nature (Hinkel et al. 2014) and require tackling the absence or poor functioning of institutions and the structural constraints that they engender through access and control levers using policies and markets and other mechanisms (Schut et al. 2016). Other examples of rights-based instruments include the protection of heritage sites, sacred sites and peace parks (IPBES 2018a). Rights-based instruments and customary norms are consistent with the aims of international and national human rights, and the critical issue of liability in the climate change problem.

1.4.3.4 Social and cultural norms

Social and cultural instruments are concerned with the communication of knowledge about conscious consumption patterns and resource-effective ways of life through awareness raising, education and communication of the quality and the provenance of land-based products. Examples of the latter include consumption choices aided by ecolabelling (Section 1.4.3.2) and certification. Cultural indicators (such as social capital, cooperation, gender equity, women's knowledge, socio-ecological mobility) contribute to the resilience of social-ecological systems (Sterling et al. 2017). Indigenous communities (such as the Inuit and Tsleil Waututh Nation in Canada) that continue to maintain traditional foods exhibit greater dietary quality and adequacy (Sheehy et al. 2015). Social and cultural instruments also include approaches to self-regulation and voluntary agreements, especially with respect to environmental management and land resource use. This is becoming especially irrelevant for the increasingly important domain of corporate social responsibility (Halkos and Skouloudis 2016).

1.5 The interdisciplinary nature of the SRCCL

Assessing the land system in view of the multiple challenges that are covered by the SRCCL requires a broad, inter-disciplinary perspective. Methods, core concepts and definitions are used differently in different sectors, geographic regions, and across academic communities addressing land systems, and these concepts and approaches to research are also undergoing a change in their interpretation through time. These differences reflect varying perspectives, in nuances or emphasis, on land as components of the climate and socio-economic systems. Because of its inter-disciplinary nature, the SRCCL can take advantage of these varying perspectives and the diverse methods that accompany them. That way, the report aims to support decision-makers across sectors and world regions in the interpretation of its main findings and support the implementation of solutions.

Frequently Asked Questions

FAQ 1.1 | What are the approaches to study the interactions between land and climate?

Climate change shapes the way land is able to support supply of food and water for humans. At the same time the land surface interacts with the overlying atmosphere, thus human modifications of land use, land cover and urbanisation affect global, regional and local climate. The complexity of the land–climate interactions requires multiple study approaches embracing different spatial and temporal scales. Observations of land atmospheric exchanges, such as of carbon, water, nutrients and energy can be carried out at leaf level and soil with gas exchange systems, or at canopy scale by means of micrometeorological techniques (i.e. eddy covariance). At regional scale, atmospheric measurements by tall towers, aircraft and satellites can be combined with atmospheric transport models to obtain spatial explicit maps of relevant greenhouse gases fluxes. At longer temporal scale (>10 years) other approaches are more effective, such as tree-ring chronologies, satellite records, population and vegetation dynamics and isotopic studies. Models are important to bring information from measurement together and to extend the knowledge in space and time, including the exploration of scenarios of future climate–land interactions.

FAQ 1.2 | How region-specific are the impacts of different land-based adaptation and mitigation options?

Land-based adaptation and mitigation options are closely related to region-specific features for several reasons. Climate change has a definite regional pattern with some regions already suffering from enhanced climate extremes and others being impacted little, or even benefiting. From this point of view increasing confidence in regional climate change scenarios is becoming a critical step forward towards the implementation of adaptation and mitigation options. Biophysical and socio-economic impacts of climate change depend on the exposures of natural ecosystems and economic sectors, which are again specific to a region, reflecting regional sensitivities due to governance. The overall responses in terms of adaptation or mitigation capacities to avoid and reduce vulnerabilities and enhance adaptive capacity, depend on institutional arrangements, socio-economic conditions, and implementation of policies, many of them having definite regional features. However global drivers, such as agricultural demand, food prices, changing dietary habits associated with rapid social transformations (i.e. urban vs rural, meat-eating vs vegetarian) may interfere with region-specific policies for mitigation and adaptation options and need to be addressed at the global level.

FAQ 1.3 | What is the difference between desertification and land degradation? And where are they happening?

The difference between land degradation and desertification is geographic. Land degradation is a general term used to describe a negative trend in land condition caused by direct or indirect human-induced processes (including anthropogenic climate change). Degradation can be identified by the long-term reduction or loss in biological productivity, ecological integrity or value to humans. Desertification is land degradation when it occurs in arid, semi-arid, and dry sub-humid areas, which are also called drylands. Contrary to some perceptions, desertification is not the same as the expansion of deserts. Desertification is also not limited to irreversible forms of land degradation.

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Appendix

Table Appendix 1.1 | Observations related to variables indicative of land management (LM), and their uncertainties.

LM-related process	Observations methodology	Scale of observations (space and time)	Uncertainties[2]	Pros and cons	Select literature
GHG emissions	Micrometeorological fluxes (CO_2) Micrometeorological fluxes (CH_4) Micrometeorological fluxes (N_2O)	1–10 ha 0.5 hr – >10 y	5–15% 10–40% 20–50%	**Pros** – Larger footprints – Continuous monitoring – Less disturbance on monitored system – Detailed protocols **Cons** – Limitations by fetch and turbulence scale – Not all trace gases	Richardson et al. 2006; Luyssaert et al. 2007; Foken and Napo 2008; Mauder et al. 2013; Peltola et al. 2014; Wang et al. 2015; Rannik et al. 2015; Campioli et al. 2016; Rannik et al. 2016; Wang et al. 2017a; Brown and Wagner-Riddle 2017; Desjardins et al. 2018
	Soil chambers (CO_2) Soil chambers (CH_4) Soil chambers (N_2O)	0.01–1 ha 0.5 hr – 1 y	5–15% 5–25% 53–100%[3]	**Pros** – Relatively inexpensive – Possibility of manipulation experiments – Large range of trace gases **Cons** – Smaller footprint – Complicated upscaling – Static pressure interference	Vargas and Allen 2008; Lavoie et al. 2015; Barton et al. 2015; Dossa et al. 2015; Ogle et al. 2016; Pirk et al. 2016; Morin et al. 2017; Lammirato et al. 2018
	Atmospheric inversions (CO_2) Atmospheric inversions (CH_4)	Regional 1 – >10 y	50% 3–8%	**Pros** – Integration on large scale – Attribution detection (with 14C) – Rigorously derived uncertainty **Cons** – Not suited at farm scale – Large high-precision observation network required	Wang et al. 2017b Pison et al. 2018
Carbon balance	Soil carbon point measurements	0.01–1 ha >5 y	5–20%	**Pros** – Easy protocol – Well established analytics **Cons** – Need high number of samples for upscaling – Detection limit is high	Chiti et al. 2018; Castaldi et al. 2018; Chen et al. 2018; Deng et al. 2018
	Biomass measurements	0.01–1 ha 1–5 y	2–8%	**Pros** – Well established allometric equations – High accuracy at plot level **Cons** – Difficult to scale up – Labour intensive	Pelletier et al. 2012; Henry et al. 2015; Vanguelova et al. 2016; Djomo et al. 2016; Forrester et al. 2017; Xu et al. 2017Marziliano et al. 2017; Clark et al. 2017; Disney et al. 2018; Urbazaev et al. 2018; Paul et al. 2018

2 Uncertainty here is defined as the coefficient of variation CV. In the case of micrometeorological fluxes they refer to random errors and CV of daily average.

3 >100 for fluxes less than 5 $gN_2O\text{-}N\ ha^{-1}\ d^{-1}$.

LM-related process	Observations methodology	Scale of observations (space and time)	Uncertainties[2]	Pros and cons	Select literature
Water balance	Soil moisture (IoT sensors, Cosmic rays, Thermo-optical sensing etc.)	0.01 ha – regional 0.5 hr – <1 y	3–5% vol	**Pros** – New technology – Big data analytics – Relatively inexpensive **Cons** – Scaling problems	Yu et al. 2013; Zhang and Zhou 2016; Iwata et al. 2017; McJannet et al. 2017; Karthikeyan et al. 2017; Iwata et al. 2017; Cao et al. 2018; Amaral et al. 2018; Moradizadeh and Saradjian 2018; Strati et al. 2018
	Evapotranspiration	0.01 ha – regional 0.5 hr – >10 y	10–20%	**Pros** – Well established methods – Easy integration in models and DSS **Cons** – Partition of fluxes need additional measurements	Zhang et al. 2017; Papadimitriou et al. 2017; Kaushal et al. 2017; Valayamkunnath et al. 2018; Valayamkunnath et al. 2018; Tie et al. 2018; Wang et al. 2018
Soil erosion	Sediment transport	1 ha – regional 1d – >10y	21–34%	**Pros** – Long history of methods – Integrative tools **Cons** – Validation is lacking – Labour intensive	Efthimiou 2018; García-Barrón et al. 2018; Fiener et al. 2018
Land cover	Satellite	0.01 ha – regional 1 d – >10 y	16–100%	**Pros** – Increasing platforms available – Consolidated algorithms **Cons** – Need validation – Lack of common land-use definitions	Olofsson et al. 2014; Liu et al. 2018; Yang et al. 2018

Table Appendix 1.2 | Possible uncertainties decision-making faces (following Hansson and Hadorn 2016).

Type	Knowledge gaps	Understanding the uncertainties
Uncertainty of consequences	Do the model(s) adequately represent the target system? What are the numerical values of input parameters, boundary conditions, or initial conditions? What are all potential events that we would take into account if we were aware of them? Will future events relevant for our decisions, including expected impacts from these decisions, in fact take place?	Ensemble approaches; downscaling Benchmarking, sensitivity analyses Scenario approaches
Moral uncertainty	How to (ethically) evaluate the decisions? What values to base the decision on (often unreliable ranking of values not doing justice to the range of values at stake, see Sen 1992), including choice of discount rate, risk attitude (risk aversion, risk neutral, …). Which ethical principles? (i.e. utilitarian, deontic, virtue, or other?).	Possibly scenario analysis; Identification of lock-in effects and path-dependency (e.g., Kinsley et al. 2016)
Uncertainty of demarcation	What are the options that we can actually choose between? (not fully known because 'decision costs' may be high, or certain options are not 'seen' as they are outside current ideologies). How can the mass of decisions be divided into individual decisions? e.g., how this influences international negotiations and the question who does what and when (cp. Hammond et al. 1999).	Possibly scenario analysis
Uncertainty of consequences and uncertainty of demarcation	What effects does a decision have when combined with the decisions of others? (e.g., other countries may follow the inspiring example in climate reduction of country X, or they may use it solely in their own economic interest).	Games
Uncertainty of demarcation and moral uncertainty	How would we decide in the future? (Spohn 1977; Rabinowicz 2002).	

References to Appendix

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