INTERGOVERNMENTAL PANEL ON climate change

IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems

Technical Summary

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Contents

TS. 0. Introduction

This Technical Summary to the IPCC Special Report on Climate Change and Land[1] (SRCCL) comprises a compilation of the chapter executive summaries illustrated with figures from the report. It follows the structure of the SRCCL (Figure TS. 2) and is presented in seven parts. TS.1 (Chapter 1) provides a synopsis of the main issues addressed in the Special Report, introducing key concepts and definitions and highlighting where the report builds on previous publications. TS.2 (Chapter 2) focuses on the dynamics of the land-climate system (Figure TS.1). It assesses recent progress towards understanding the impacts of climate change on land, and the feedbacks land has on climate and which arise from altered biogeochemical and biophysical fluxes between the atmosphere and the land surface. TS.3 (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. TS.4 (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 improved land management, which is expected to improve resilience to climate change, mitigate climate change, and ensure food security for generations to come. TS.5 (Chapter 5) focuses on food security, with an assessment of the risks and opportunities that climate change presents to food systems. It considers how mitigation and adaptation can contribute to both human and planetary health. TS.6 (Chapter 6) introduces options for responding to the challenges of desertification, land degradation and food security and evaluates the trade-offs for sustainable land management, climate adaptation and mitigation, and the sustainable development goals. TS7 Further assesses decision making and policy responses to risks in the climate-land-human system.

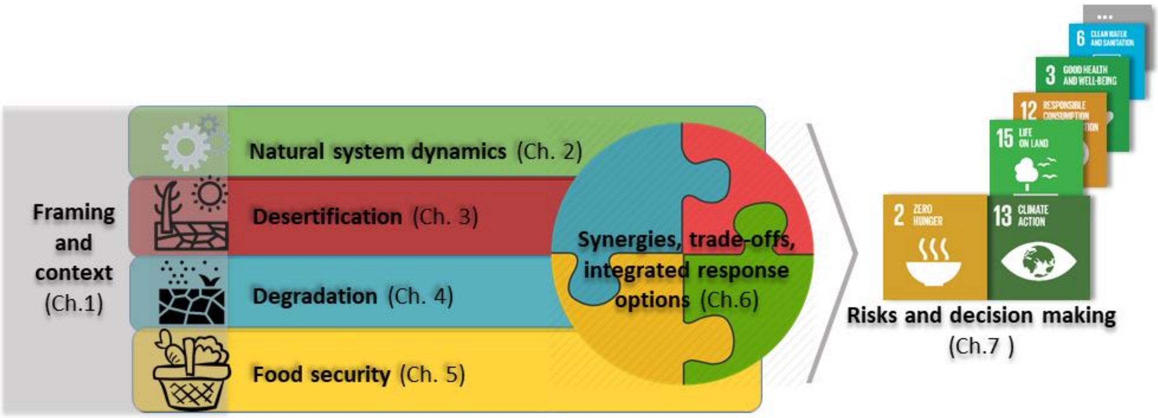

Figure TS. 2 Overview of the IPCC Special Report on Climate Change and Land (SRCCL).

TS.1. Framing and Context

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

[1] FOOTNOTE: The full title of the report is the "IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems"

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 75–85 trillion USD in 2011 (based on USD 2007 values) (*low confidence*). This substantially exceeds the annual World GDP (*high 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*). {1.2.1}

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 9-fold, 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*) (Figure TS. 3). {1.2.2; Figure SPM1}

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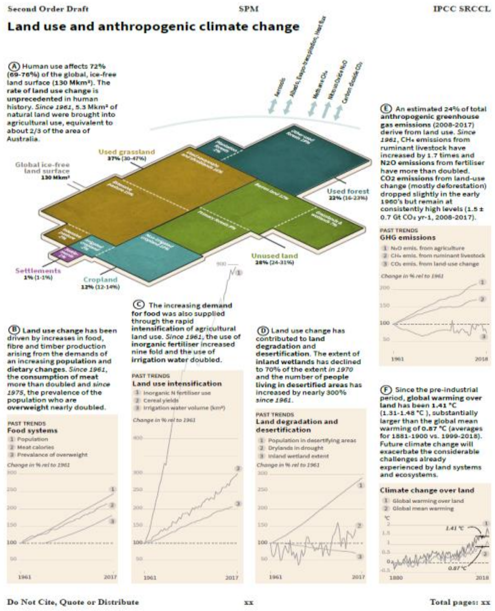

[SPM1]

Figure TS. 3 Land use and anthropogenic climate change. A representation of the land use and anthropogenic climate change covered in this assessment report. A: The central illustration depicts how human use affects 72% (69-76%) of the global, ice-free land area. The surface tiles show the extent of current (in ca. 2015) global land use and management, aggregated into five broad categories and associated uncertainty ranges. "Used land" refers to settlements, managed grassland, forest land and cropland. "Unused land" refers to barren land, unmanaged grassland and forest land. Note that these categories are not intended to be directly relatable to the land cover types used for GHG inventory purposes {1.2, Table 1.1}[2]. B: Agricultural areas have increased to meet the demand arising from population growth, increasing consumption of animal products, growing food waste and overconsumption indicated by the proportion of the global population that is overweight (body mass index > 25 kg/m^2) {5.1, 5.2}. C: Increasing food production has led to rapid land use intensification, including increases in the use of nitrogen fertiliser and irrigation water that have supported the growth in cereal yields {1.2, Figure 1.1}. 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. D: Land use change has led to substantial losses in the extent of inland wetlands {4.3.1, 4.7.1}. Dryland areas are under increasing pressures both from the increasing number of people living in these areas and from the increase in droughts {3.2}[3]. E: Land use change and intensification has contributed to CO_2 emissions, primarily through deforestation, N_2O emissions from agriculture and CH_4 emissions from ruminant livestock {2.3}[4]. The various exchanges between the land surface and the atmosphere including the emission and removals of GHG, exchanges related to the land-surface energy balance and aerosols are indicated by arrows {2.4, 2.5}. F: Warming over land is more rapid than the global mean temperature change {2.2}[5]. The warming from the late 19th century (1881-1900) to present (1999-2018), was 1.41°C (1.31°C to 1.51°C]) compared to a global mean of 0.86ºC {Table 2.1}.

[2]FOOTNOTE: A: Land use and management classification based on the data and approaches described in Table 1.1. Intensive pasture is defined as having a livestock density greater than 100 animals/km². Used forest was calculated as total forest area minus unused forest area.

[3]FOOTNOTE: D: Areas undergoing human caused desertification, after accounting for precipitation variability and CO_2 fertilisation, are identified in (Le et al. 2016). Population data for these areas are from HYDE3.2 (Goldewijk et al. 2017). The 12-month accumulation Global Precipitation Climatology Centre Drought Index (Ziese et al. 2014) was extracted for drylands. 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 trends (WET) index was developed by aggregating data from 2130 time series that report changes in local wetland area over time. Dryland areas were defined using TerraClimate precipitation and potential evapotranspiration (1980-2015) to identify areas where the Aridity Index is below 0.65.

[4]FOOTNOTE: E: Sources: N_2O from agricultural activities and CH_4 from enteric fermentation: Net-land use change emissions of CO_2 are from the annual Global Carbon Budget, using the mean of two bookkeeping models (Le Quéré et al. 2018). See Section 2.3 for a discussion of uncertainties and other emissions estimates.

[5]FOOTNOTE: F: The warming curves are averages of four historical estimates (1881-1900) to present (1999-2018). Note that Figure 2.2 depicts the change of land-surface air temperature (LSAT) and global mean surface temperature (GMST) since the preindustrial period 1850–1900 and for the entire 1850-2018 period. The thickness of lines in Figure 2.2 represents the spread between the annual median estimates from the respective datasets and panel F of SPM1 depicts the mean values of those medians.

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 1999–2018 was 1.41°C higher than for the period 1881–1900, and 0.54°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*). {1.2.2}

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*). {1.2.2, 1.3.1, 1.4.2-1.4.6, Cross-Chapter Box 1: Scenarios in Chapter 1}

Rapid reductions in anthropogenic greenhouse gas 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 that depend on land (*high confidence*). {1.4.1, Cross-Chapter Box 2: Implications of large-scale conversion from non-forest to forest land 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. {1.3.1 1.4.2, 1.4.3, 1.4.4, 1.4.5, 1.4.6}

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 more than 30% of harvested materials) (*high 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*). {1.3.1, 1.4.3}

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*). {1.5.1, 1.5.2}

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*). {1.4, 1.5}

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*). {1.4.5, 1.5.1, 1.5.2, 1.5.3}

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. {1.3.2, Cross-Chapter Box 1: Scenarios in Chapter 1}

TS.2. Land-Climate Interactions

It is certain that globally averaged land surface air temperature (LSAT) has risen faster than the global mean surface temperature (i.e., combined LSAT and sea surface temperature) from preindustrial (1850–1900) to present day (1999–2018). According to the single longest and most extensive dataset, the LSAT increase between the preindustrial period and present day was 1.52°C (the *very likely* range of 1.39°C to 1.66°C). For the 1880–2018 period, when four independently produced datasets exist, the LSAT increase was 1.41℃ (1.31℃–1.51℃), where the range represents the spread in the datasets' median estimates. Analyses of paleo records, historical observations, model simulations, and underlying physical principles are all in agreement that LSATs are increasing at a higher rate than SST as a result of differences in evaporation, land-climate feedbacks, and changes in the aerosol forcing over land (*very high confidence*). For the 2000–2016 period, the land-to-ocean warming ratio (about 1.6) is in close agreement between different observational records and the CMIP5 climate model simulations (the *likely* range of 1.54 to 1.81). (Figure TS. 4). {2.3.1}

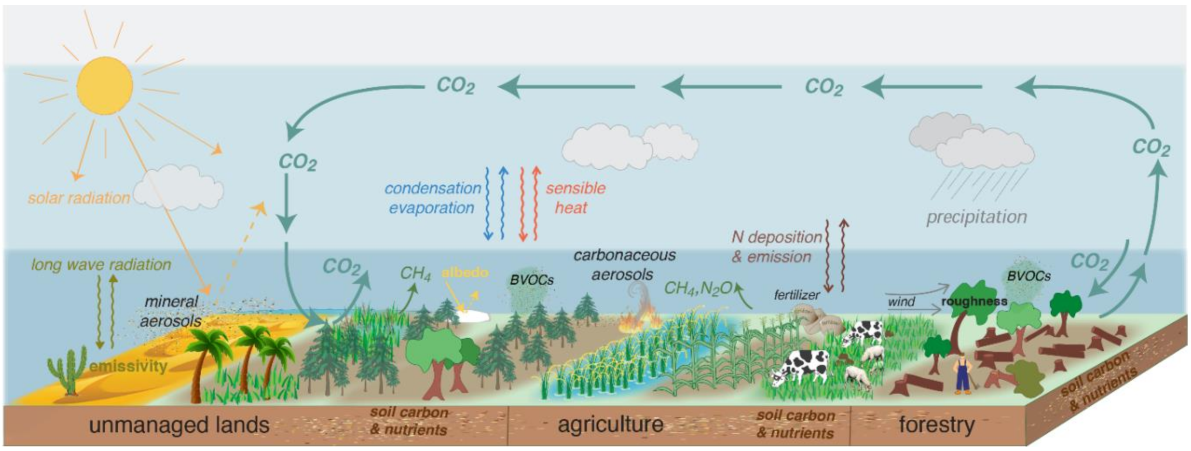

Figure TS. 4 The structure and functioning of managed and unmanaged ecosystems that affect local, regional, and global climate. Land surface characteristics such as albedo and emissivity determine the amount of solar and long-wave radiation absorbed by land and reflected or emitted to the atmosphere. Surface roughness influences turbulent exchanges of momentum, energy, water, and biogeochemical tracers. Land ecosystems modulate the atmospheric composition through emissions and removals of many GHGs and precursors of SLCFs, including biogenic volatile organic compounds (BVOCs) and mineral dust. Atmospheric aerosols formed from these precursors affect regional climate by altering amounts of precipitation and of radiation reaching land surfaces through their role in clouds physics.

Anthropogenic warming has resulted in shifts of climate zones, primarily as an increase in dry climates and decrease of polar climates (*high confidence*). Ongoing warming is projected to result in new, hot climates in tropical regions and to shift climate zones poleward in the mid- to high latitudes and upward in regions of higher elevation (*high confidence*). Ecosystems in these regions will become increasingly exposed to temperature and rainfall extremes beyond climate regimes they are currently adapted to (*high confidence*), which can alter their structure, composition and functioning. Additionally, high-latitude warming is projected to accelerate permafrost thawing and increase disturbance in boreal forests through abiotic (e.g., drought, fire) and biotic (e.g., pests, disease) agents (*high confidence*). {2.3.1, 2.3.2, 2.6.3}

Globally, greening trends (trends of increased photosynthetic activity in vegetation) have increased over the last 2-3 decades by 22–33%, particularly over China, India, many parts of Europe, central North America, southeast Brazil and southeast Australia (*high confidence*). This results from a combination of direct (i.e., land use and management, forest conservation and expansion) and indirect factors (i.e., CO_2 fertilisation, extended growing season, global warming, nitrogen deposition, increase of diffuse radiation) linked to human activities (*high confidence*). Browning trends (trends of decreasing photosynthetic activity) are projected in many regions where increases in drought and heat waves are projected in a warmer climate. There is *low confidence* in the projections of global greening and browning trends. {2.3.4, Cross-Chapter Box 4: Climate Change and Urbanisation in Chapter 2}

The frequency and intensity of some extreme weather and climate events have increased as a consequence of global warming and will continue to increase under medium and high emission scenarios (*high confidence*). Recent heat-related events, e.g., heat waves, have been made more frequent or intense due to anthropogenic greenhouse gas emissions in most land regions and the frequency and intensity of drought has increased in Amazonia, north-eastern Brazil, the Mediterranean, Patagonia, most of Africa and north-eastern China (*medium confidence*). Heat waves are projected to increase in frequency, intensity and duration in most parts of the world (*high confidence*) and drought frequency and intensity is projected to increase in some regions that are already drought prone, predominantly in the Mediterranean, central Europe, the southern Amazon and southern Africa (*medium confidence*). These changes will impact ecosystems, food security and land processes including greenhouse gas (GHG) fluxes (*high confidence*). {2.3.5}

Climate change is playing an increasing role in determining wildfire regimes along-side human activity (*medium confidence*), with future climate variability expected to enhance the risk and severity of wildfires in many biomes such as tropical rainforests (*high confidence*). Fire weather seasons have lengthened globally between 1979 and 2013 (*low confidence*). Global land area burned has declined in recent decades, mainly due to less burning in grasslands and savannahs (*high confidence*). While drought remains the dominant driver of fire emissions, there has recently been increased fire activity in some tropical and temperate regions during normal to wetter than average years due to warmer temperatures that increase vegetation flammability (*medium confidence*). The boreal zone is also experiencing larger and more frequent fires, and this may increase under a warmer climate (*medium confidence*). {Cross-Chapter Box 4: Climate Change and Urbanisation in Chapter 2}

Terrestrial greenhouse gas fluxes on unmanaged and managed lands

Agriculture, Forestry and Other Land Use (AFOLU) is a significant net source of GHG emissions (*high confidence*), contributing to about 22% of anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) combined as CO_2 equivalents in 2007 to 2016 (*medium confidence*). AFOLU results in both emissions and removals of CO_2, CH_4, and N_2O to and from the atmosphere (*high confidence*). These fluxes are affected simultaneously by natural and human drivers, making it difficult to separate natural from anthropogenic fluxes (*very high confidence*). {2.4}

The total net land-atmosphere flux of CO_2 on both managed and unmanaged lands *very likely* provided a global net removal from 2008 to 2017 according to models, (-6.2 ± 3.7 $GtCO_2\ yr^{-1}$, *medium confidence*). This net removal is comprised of two major components: i) modelled net anthropogenic emissions from AFOLU are *likely* 5.5 ± 2.6 $GtCO_2\ yr^{-1}$ driven by land cover change, including deforestation and afforestation/reforestation, and wood harvesting (accounting for about 13% of total net anthropogenic emissions of CO_2) (*medium confidence*); and ii) modelled net removals due to non-anthropogenic processes are *likely* 11.7 ± 2.6 $GtCO_2\ yr^{-1}$ on managed and unmanaged lands, driven by environmental changes such as increasing CO_2, nitrogen deposition, and changes in climate (accounting for a removal of 29% of the CO_2 emitted from all anthropogenic activities (fossil fuel, industry and AFOLU) (*medium confidence*). {2.4.1}

The anthropogenic emissions of CO_2 from AFOLU reported in countries' GHG inventories were 0.1 ± 1.0 $GtCO_2\ yr^{-1}$ globally during 2005 to 2014 (*low confidence*), much lower than emission estimates from global models of 5.1 ± 2.6 $GtCO_2\ yr^{-1}$ over the same time period. Reconciling these differences can support consistency and transparency in assessing global progress towards meeting modelled mitigation pathway such as under the Paris Agreement's global stocktake (*medium confidence*). This discrepancy is consistent with understanding of the different approaches used to defining anthropogenic fluxes. Inventories consider larger areas of forested lands as managed than models do, and report all fluxes on managed lands as anthropogenic, including a large net sink due to the indirect effects of changing environmental conditions (e.g., climate change, and change in atmospheric CO_2 and N). In contrast, the models assign part of this indirect forest sink to the non-anthropogenic sink on unmanaged lands. {2.4.1}

The gross emissions from AFOLU (one third of total global emissions) are more indicative of mitigation potential of reduced deforestation than the global net emissions (13% of total global emissions), which include compensating deforestation and afforestation fluxes (*high confidence*). The net flux of CO_2 from AFOLU is composed of two opposing gross fluxes: gross emissions (20 $GtCO_2\ yr^{-1}$) from deforestation, cultivation of soils, and oxidation of wood products; and gross removals (-14 $GtCO_2\ yr^{-1}$) largely from forest growth following wood harvest and agricultural abandonment (*medium confidence*) (Figure TS. 5).{2.4.1}

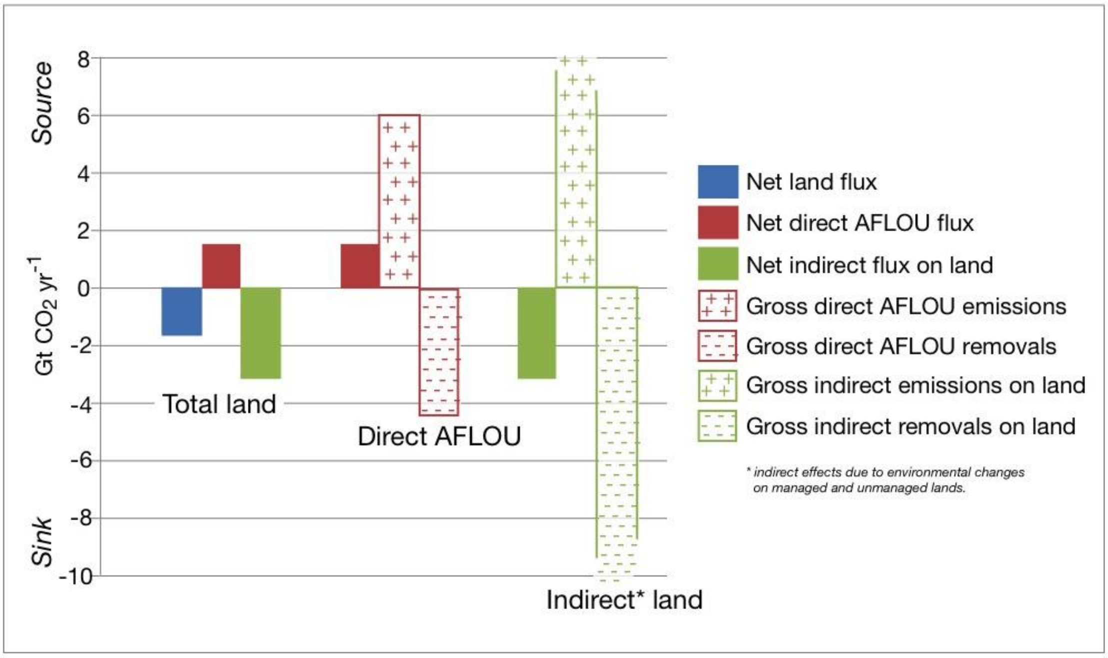

Figure TS. 5 Net and gross fluxes of CO_2 from land (annual averages for 2008-2017). [Left]: The total net flux of CO2 between land and atmosphere (blue) is shown with its two component fluxes: Net AFOLU emissions (red) and the net land sink (green) due to indirect environmental effects and natural effects on managed and unmanaged lands. [Middle]: The gross emissions and removals contributing to the net AFOLU flux. [Right]: The gross emissions and removals contributing to the land sink.

Land is a net source of CH_4, accounting for 61% of anthropogenic CH_4 emissions for the 2005–2015 period (*medium confidence*). The pause in the rise of atmospheric CH_4 concentrations between 2000 and 2006 and the subsequent renewed increase appear to be partially associated with land use and land use change. The recent depletion trend of the ^{13}C isotope in the atmosphere indicates that higher biogenic sources explain part of the current CH_4 increase and that biogenic sources make up a larger proportion of the source mix than they did before 2000 (*high confidence*). In agreement with the findings of AR5, tropical wetlands and peatlands continue to be important drivers of inter-annual variability and current CH_4 concentration increases (*medium evidence, high agreement*). Ruminants and the expansion of rice cultivation are also important contributors to the current trend (*medium evidence, high agreement*). There is significant and ongoing accumulation of CH_4 in the atmosphere (*very high confidence*). {2.4.2}

AFOLU is the main anthropogenic sources of N_2O primarily due to nitrogen (N) application to soils (*high confidence*). In croplands, the main driver of N_2O emissions is a lack of synchronisation between crop N demand and soil N supply, with approximately 50% of the N applied to agricultural land not taken up by the crop. Cropland soils emit over 3 Mt N_2O-N yr^{-1} (*medium confidence*). Because the response of N_2O emissions to fertiliser application rates is non-linear, in regions of the World where low N application rates dominate, such as sub-Saharan Africa and parts of Eastern Europe, increases in N fertiliser use would generate relatively small increases in agricultural N_2O emissions. Decreases in application rates in regions where application rates are high and exceed crop demand for parts of the growing season will have very large effects on emissions reductions (*medium evidence, high agreement*). {2.4.3}

While managed pastures make up only one-quarter of grazing lands, they contributed more than three-quarters of N_2O emissions between 1961 and 2014 with rapid recent increases of N inputs resulting in disproportionate growth in emissions from these lands (*medium confidence*). Grazing lands (pastures and rangelands) are responsible for more than one-third of total anthropogenic N_2O emissions or more than one-half of agricultural emissions (*high confidence*). Emissions are largely from North America, Europe, East Asia, and South Asia, but hotspots are shifting from Europe to southern Asia (*medium confidence*). {2.4.3}

Increased emissions from vegetation and soils due to climate change in the future are expected to counteract potential sinks due to CO_2 fertilisation *(low confidence).* Responses of vegetation and soil organic carbon (SOC) to rising atmospheric CO_2 concentration and climate change are not well constrained by observations *(medium confidence)*. Nutrient (e.g., nitrogen, phosphorus) availability can limit future plant growth and carbon storage under rising CO_2 (*high confidence*). However, new evidence suggests that ecosystem adaptation through plant-microbe symbioses could alleviate some nitrogen limitation (*medium evidence, high agreement*). Warming of soils and increased litter inputs will accelerate carbon losses through microbial respiration (*high confidence*). Thawing of high-latitude/altitude permafrost will increase rates of SOC loss and change the balance between CO_2 and CH_4 emissions (*medium confidence*). The balance between increased respiration in warmer climates and carbon uptake from enhanced plant growth is a key uncertainty for the size of the future land carbon sink *(medium confidence*). {2.4.1, 2.8.2, Box 2.3}

Biophysical and biogeochemical land forcing and feedbacks to the climate system

Changes in land conditions from human use or climate change in turn affect regional and global climate *(high confidence)*. On the global scale, this is driven by changes in emissions or removals of CO_2, CH_4, and N_2O by land (biogeochemical effects) and by changes in the surface albedo (*very high confidence*). Any local land changes that redistribute energy and water vapour between the land and the atmosphere influence regional climate (biophysical effects; *high confidence*). However, there is *no confidence* in whether such biophisical effects influence global climate. {2.2, 2.4, 2.6.1, 2.6.2}

Changes in land conditions modulate the likelihood, intensity and duration of many extreme events including heat waves *(high confidence)* and heavy precipitation events *(medium confidence)*. Dry soil conditions favour or strengthen summer heat wave conditions through reduced evapotranspiration and increased sensible heat. By contrast wet soil conditions, for example from irrigation, or crop management practices that maintain a cover crop all year round, can dampen extreme warm events through increased evapotranspiration and reduced sensible heat. Droughts can be intensified by poor land management. Urbanisation increases extreme rainfall events over or downwind of cities (*medium confidence*). {2.6.1, 2.6.2, 2.6.3}

Historical changes in anthropogenic land cover have resulted in a mean annual global warming of surface air from biogeochemical effects *(very high confidence)*, dampened by a cooling from biophysical effects (*medium confidence*). Biogeochemical warming results from increased emissions of GHGs by land, with model-based estimates of +0.20±0.05°C (global climate models) and +0.24±0.12°C (dynamic global vegetation models, DGVMs) as well as an observation-based estimate of +0.25±0.10°C. A net biophysical cooling of –0.10±0.14°C has been derived from global climate models in response to the increased surface albedo and decreased turbulent heat fluxes, but it is smaller than the warming effect from land-based emissions. However when both biogeochemical and biophysical effects are accounted for within the same global climate model, the models do not agree on the sign of the net change in mean annual surface air temperature. {2.4, 2.6.1, Box 2.1}

The future projected changes in anthropogenic land cover that have been examined for AR5 would result in a biogeochemical warming and a biophysical cooling whose magnitudes depend on the scenario *(high confidence)*. Biogeochemical warming has been projected for RCP8.5 by both global climate models (+0.20±0.15°C) and DGVMs (+0.28±0.11°C) (*high confidence*). A global biophysical cooling of 0.10±0.14°C is estimated from global climate models, and projected to dampen the land-based warming (*low confidence*). For RCP4.5 the biogeochemical warming estimated from global climate models (+0.12±0.17°C) is stronger than the warming estimated by DGVMs (+0.01±0.04°C) but based on *limited evidence*, as is the biophysical cooling (–0.10±0.21°C). {2.6.2}

Regional climate change can be dampened or enhanced by changes in local land cover and land use (*high confidence*) but this depends on the location and the season (*high confidence*). In boreal regions, for example, where projected climate change will migrate treeline northward, increase the growing season length and thaw permafrost, regional winter warming will be enhanced by decreased surface albedo and snow, whereas warming will be dampened during the growing season due to larger evapotranspiration (*high confidence*). In the tropics, wherever climate change will increase rainfall, vegetation growth and associated increase in evapotranspiration will result in a dampening effect on regional warming (*medium confidence*). {2.6.2, 2.6.3}

According to model-based studies, changes in local land cover or available water from irrigation affect climate in regions as far as few hundreds of kilometres downwind (*high confidence*). The local redistribution of water and energy following the changes on land affect the horizontal and vertical gradients of temperature, pressure and moisture, thus alter regional winds and consequently moisture and temperature advection and convection, and this affects precipitation. {2.6.2, 2.6.4, Cross-Chapter Box 4: Climate Change and Urbanisation in Chapter 2}

Future increases in both climate change and urbanisation will enhance warming in cities and their surroundings (urban heat island), especially during heat waves (*high confidence*). Urban and peri-urban agriculture, and more generally urban greening, can contribute to mitigation (*medium confidence*) as well as to adaptation (*high confidence*), with co-benefits for food security and reduced soil-water-air pollution. {Cross-Chapter Box 4: Climate Change and Urbanisation in Chapter 2}

Regional climate is strongly affected by natural land aerosols *(medium confidence)* (e.g., mineral dust, black, brown and organic carbon), but there is *low confidence* in historical trends, interannual and decadal variability, and future changes. Forest cover affects climate through emissions of biogenic volatile organic compounds (BVOC) and aerosols (*low confidence).* The decrease in the emissions of BVOC resulting from the historical conversion of forests to cropland has resulted in a positive radiative forcing through direct and indirect aerosol effects, a negative radiative forcing through the reduction in the atmospheric lifetime of methane and it has contributed to increased ozone concentrations in different regions (*low confidence*). {2.5, 2.6}

Consequences for the climate system of land-based adaptation and mitigation options, including carbon dioxide removal (negative emissions)

About one quarter of the 2030 mitigation pledged by countries in their initial Nationally Determined Contributions (NDCs) under the Paris Agreement is expected to come from land-based mitigation options *(medium confidence)*. Most of the Nationally Determined Contributions (NDCs) submitted by countries include land-based mitigation, although many lack details. Several refer explicitly to reduced deforestation and forest sinks, while a few include soil carbon sequestration, agricultural management and bioenergy. Full implementation of NDCs (submitted by February 2016) is expected to result in net removals of 0.4–1.3 $GtCO_2$ y^{-1} in 2030 compared to the net flux in 2010, where the range represents low to high mitigation ambition in pledges, not uncertainty in estimates (*medium confidence*). {2.7.3}

Several mitigation response options have technical potential for >3 $GtCO_2$-eq yr^{-1} by 2050 through reduced emissions and Carbon Dioxide Removal (CDR) *(high confidence)*, some of which compete for land and other resources, while others may reduce the demand for land *(high confidence)*. Estimates of the technical potential of individual response options are not necessarily additive. The largest potential for reducing AFOLU emissions are through reduced deforestation and forest degradation (0.4–5.8 $GtCO_2$-eq yr^{-1}) *(high confidence),* a shift towards plant-based diets (0.7–8.0 $GtCO_2$-eq yr^{-1}) *(high confidence)* and reduced food and agricultural waste (0.8–4.5 CO_2-eq yr^{-1}) *(high confidence)*. Agriculture measures combined could mitigate 0.3–3.4 $GtCO_2$-eq yr^{-1} (*medium confidence)*. The options with largest potential for CDR are afforestation/reforestation (0.5–10.1 CO_2-eq yr^{-1}) *(medium confidence)*, soil carbon sequestration in croplands and grasslands (0.4–8.6 CO_2-eq yr^{-1}) *(high confidence)* and Bioenergy with Carbon Capture and Storage (BECCS) (0.4–11.3 CO_2-eq yr^{-1}) *(medium confidence)*. While some estimates include sustainability and cost considerations, most do not include socio-economic barriers, the impacts of future climate change or non-GHG climate forcings. {2.7.1}

Response options intended to mitigate global warming will also affect the climate locally and regionally through biophysical effects *(high confidence)*. Expansion of forest area, for example, typically removes CO_2 from the atmosphere and thus dampens global warming (biogeochemical effect, *high confidence*), but the biophysical effects can dampen or enhance regional warming depending on location, season and time of day**.** During the growing season, afforestation generally brings cooler days from increased evapotranspiration, and warmer nights (*high confidence*). During the dormant season, forests are warmer than any other land cover, especially in snow-covered areas where forest cover reduces albedo (*high confidence*). At the global level, the temperature effects of boreal afforestation/reforestation run counter to GHG effects, while in the tropics they enhance GHG effects. In addition, trees locally dampen the amplitude of heat extremes (*medium confidence*). {2.6.2, 2.6.4, 2.8, Cross-Chapter Box 4: Climate Change and Urbanisation in Chapter 2}

Mitigation response options related to land use are a key element of most modelled scenarios that provide strong mitigation, alongside emissions reduction in other sectors (*high confidence*). More stringent climate targets rely more heavily on land-based mitigation options, in particular, CDR (*high confidence*). Across a range of scenarios in 2100, CDR is delivered by both afforestation (median values of -1.3, -1.7 and -2.4 $GtCO_2yr^{-1}$ for scenarios RCP4.5, RCP2.6 and RCP1.9 respectively) and bioenergy with carbon capture and storage (BECCS) (-6.5, -11 and -14.9 $GtCO_2$ yr^{-1}). Emissions of CH_4 and N_2O are reduced through improved agricultural and livestock management as well as dietary shifts away from emission-intensive livestock products by 133.2, 108.4 and 73.5 $MtCH_4$ yr^{-1}; and 7.4, 6.1 and 4.5 MtN_2O yr^{-1} for the same set of scenarios in 2100 (*high confidence*). High levels of bioenergy crop production can result in increased N_2O emissions due to fertiliser use. The Integrated Assessment Models that produce these scenarios mostly neglect the biophysical effects of land-use son global and regional warming. {2.6, 2.7.2}

Large-scale implementation of mitigation response options that limit warming to 1.5 or 2°C would require conversion of large areas of land for afforestation/reforestation and bioenergy crops, which could lead to short-term carbon losses *(high confidence)*. The change of global forest area in mitigation pathways ranges from about -0.2 to +7.2 Mkm^2 between 2010 and 2100 (median values across a range of models and scenarios: RCP4.5, RCP2.6, RCP1.9), and the land demand for bioenergy crops ranges from about 3.2–6.6 Mkm^2 in 2100 (*high confidence*). Large-scale land-based CDR is associated with multiple feasibility and sustainability constraints (Chapters 6, 7). In high carbon lands such as forests and peatlands, the carbon benefits of land protection are greater in the short-term than converting land to bioenergy crops for BECCS, which can take several harvest cycles to 'pay-back' the carbon emitted during conversion (carbon-debt), from decades to over a century *(medium confidence)* (Figure TS. 6). {2.7.2, Chapters 6, 7}

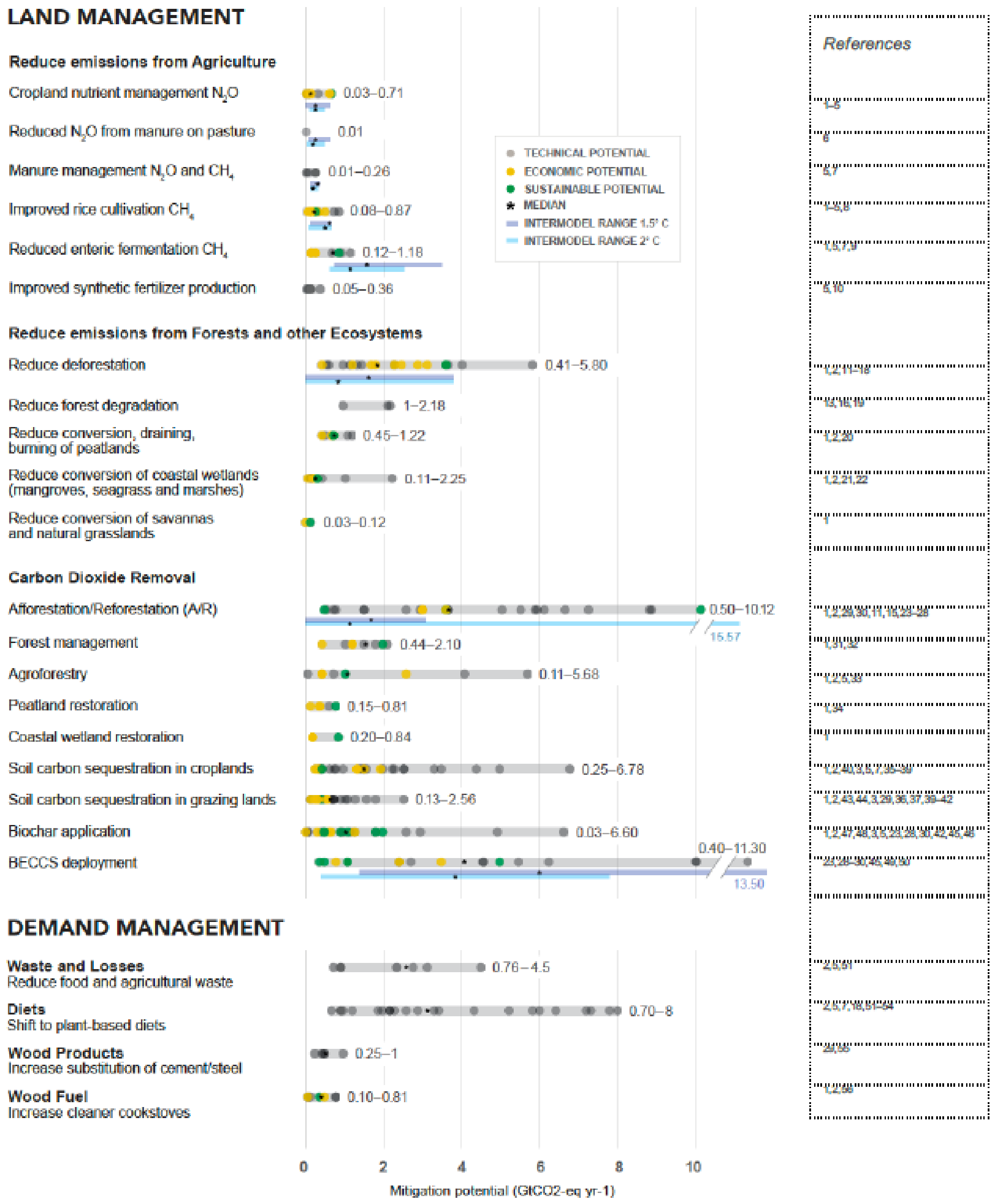

Figure TS. 6 Mitigation potential of response options in 2020-2050, measured in GtCO2-eq yr-1, adapted from(Roe et al. 2017). Mitigation potentials reflect the full range of low to high estimates from studies published after 2010, differentiated according to technical (possible with current technologies), economic (possible given economic constraints) and sustainable potential (technical or economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories with >4 data points. Only includes references that explicitly provide mitigation potential estimates in CO2-eq yr-1 (or similar derivative) by 2050. Not all options land management potentials are additive as

some may compete for land. Estimates reflect a range of methodologies (including definitions, global warming potentials and time horizons) that may not be directly comparable or additive. Results from Integrated Assessment Models are shown to compare with single option "bottom-up" estimates, in available categories from the 2°C and 1.5°C scenarios in the SSP Database (Version 2.0). The models reflect land management changes, yet in some instances, can also reflect demand-side effects from carbon prices, so may not be defined exclusively as "supply-side".

It is possible to achieve climate change targets with low need for land-demanding CDR such as BECCS, but such scenarios rely more on rapidly reduced emissions or CDR from forests, agriculture and other sectors. Terrestrial CDR has the technical potential to balance emissions that are difficult to eliminate with current technologies (including food production). Scenarios that achieve climate change targets with less need for terrestrial CDR rely on agricultural demand-side changes (diet change, waste reduction), and changes in agricultural production such as agricultural intensification. Such pathways that minimise land use for bioenergy and BECCS are characterised by rapid and early reduction of GHG emissions in all sectors, as well as earlier CDR in through afforestation. In contrast, delayed mitigation action would increase reliance on land-based CDR (*high confidence*). {2.7.2}

TS.3. Desertification

Desertification is land degradation in arid, semi-arid, and dry sub-humid areas, collectively known as drylands, resulting from many factors, including human activities and climatic variations. The range and intensity of desertification have increased in some dryland areas over the past several decades (*high confidence*). Drylands currently cover about 46.2% (±0.8%) of the global land area and are home to 3 billion people. The multiplicity and complexity of the processes of desertification make its quantification difficult. Desertification hotspots, as identified by a decline in vegetation productivity between 1980s and 2000s, extended to about 9.2% of drylands (±0.5%), affecting about 500 (±120) million people in 2015. The highest numbers of people affected are in South and East Asia, North Africa and Middle East (*low confidence*). Desertification has already reduced agricultural productivity and incomes (*high confidence*) and contributed to the loss of biodiversity in some dryland regions (*medium confidence*). In many dryland areas, spread of invasive plants has led to losses in ecosystem services (*high confidence*), while over-extraction is leading to groundwater depletion (*high confidence*) . Unsustainable land management, particularly when coupled with droughts, has contributed to higher dust storm activity, reducing human wellbeing in drylands and beyond (*high confidence*). Dust storms were associated with global cardiopulmonary mortality of about 402,000 people in a single year. Higher intensity of sand storms and sand dune movements are causing disruption and damage to transportation and solar and wind energy harvesting infrastructures (*high confidence*) (Figure TS. 7). {3.2.1, 3.2.4, 3.3.1, 3.4.1, 3.5.1, 3.5.2, 3.5.2, 3.8.3, 3.8.4}

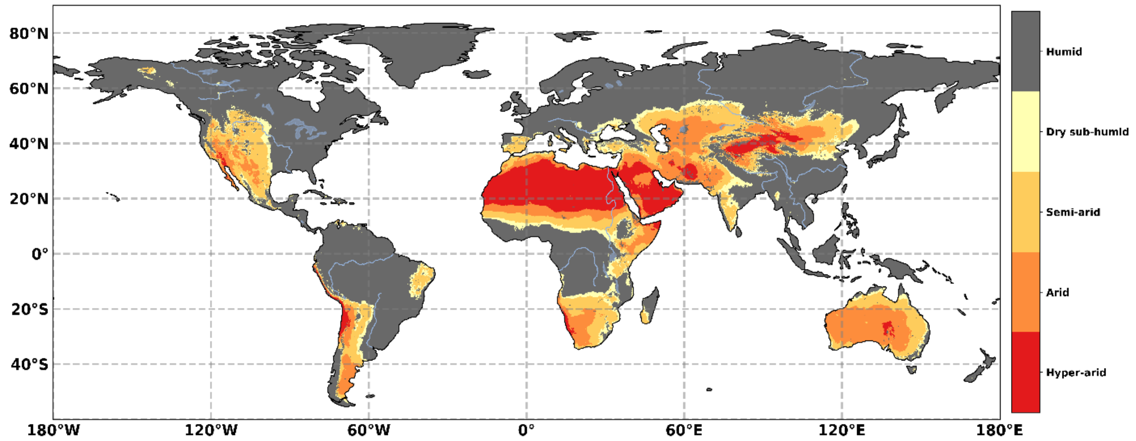

Figure TS. 7 Geographical distribution of drylands, delimited based on the Aridity Index (AI). The classification of AI is: Humid AI > 0.65, Dry sub-humid 0.50 < AI ≤ 0.65, Semi-arid 0.20 < AI ≤ 0.50, Arid 0.05 < AI ≤ 0.20, Hyper-arid AI < 0.05. Data: TerraClimate precipitation and potential evapotranspiration (1980-2015) (Abatzoglou et al., 2018).

Attribution of desertification to climate variability and change and human activities varies in space and time (*high confidence*). Climate variability and anthropogenic climate change, particularly through increases in both land surface air temperature and evapotranspiration, and decreases in precipitation, are *likely* to have played a role, in interaction with human activities, in causing desertification in some dryland areas. The major human drivers of desertification interacting with climate change are expansion of croplands, unsustainable land management practices and increased pressure on land from population and income growth. Poverty is limiting both capacities to adapt to climate change and availability of financial resources to invest in sustainable land management (SLM) (*high confidence*). {3.2.4, 3.3.2, 3.5.2}

Climate change will exacerbate several desertification processes (*medium confidence*). Although CO_2-fertilisation effect is enhancing vegetation productivity in drylands (*high confidence*), decreases in water availability have a larger effect than CO_2-fertilisation in many dryland areas. There is *high confidence* that aridity will increase in some places, but no evidence for a projected global trend in dryland aridity (*medium confidence*). The area at risk of salinisation is projected to increase in the future (*limited evidence, high agreement*). Future climate change is projected to increase the potential for water driven soil erosion in many dryland areas (*medium confidence*), leading to soil organic carbon decline in some dryland areas. {3.2.1, 3.3.2, 3.6.1, 3.6.2; 3.8.1, 3.8.3}

Risks from desertification are projected to increase due climate change (*high confidence*). Under shared socioeconomic pathway SSP2 ("Middle of the Road") at 1.5°C, 2°C and 3°C of global warming, the number of dryland population exposed (vulnerable) to various impacts related to water, energy and land sectors (e.g. water stress, drought intensity, habitat degradation) are projected to reach 951 (178) million, 1,152 (220) million and 1,285 (277) million, respectively. While at global warming of 2°C, under SSP1 (sustainability), the exposed (vulnerable) dryland population is 974 (35) million, and under SSP3 (Fragmented World) it is 1,267 (522) million. Around half of the vulnerable population is in South Asia, followed by Central Asia, West Africa and East Asia. {2.2, 3.2.1, 3.3.2, 3.6.1, 3.6.2, 7.3.2}

Desertification and climate change, both individually and in combination, will reduce the provision of dryland ecosystem services and lower ecosystem health, including losses in biodiversity (*high confidence*). Desertification and changing climate are projected to cause reductions in crop and livestock productivity (*high confidence*), modify the composition of plant species and reduce biological diversity across drylands (*medium confidence*). Rising CO_2 levels will favour more rapid expansion of some invasive plant species in some regions. A reduction in the quality and quantity of resources available to herbivores can have knock-on consequences for predators, which can potentially lead to disruptive ecological cascades (*limited evidence, low agreement*). Projected increases in temperature and the severity of drought events across some dryland areas can increase chances of wildfire occurrence (*medium confidence*). {3.2.4, 3.5.1, 3.6.2, 3.8.3}

Increasing human pressures on land combined with climate change will reduce the resilience of dryland populations and constrain their adaptive capacities (*medium confidence*). The combination of pressures coming from climate variability, anthropogenic climate change and desertification will contribute to poverty, food insecurity, and increased disease burden (*high confidence*), as well as potentially to conflicts (*low confidence*). Although strong impacts of climate change on migration in dryland areas are disputed (*medium evidence*, *low agreement*), in some places, desertification under changing climate can provide an added incentive to migrate (*medium confidence*). Women will be impacted more than men by environmental degradation, particularly in those areas with higher dependence on agricultural livelihoods (*medium evidence*, *high agreement*). {3.5.2, 3.7.2}

Desertification exacerbates climate change through several mechanisms such as changes in vegetation cover, sand and dust aerosols and greenhouse gas fluxes (***high confidence***). **The extent of areas in which dryness controls CO_2 exchange (rather than temperature) has increased by 6% between 1948-2012, and is projected to increase by at least another 8% by 2050 if the expansion continues at the same rate. In these areas, net carbon uptake is about 27% lower than in other areas (*low confidence*).** Desertification also tends to increase albedo, decreasing energy available at the surface and associated surface temperatures, producing a negative feedback on climate change (*high confidence*). Through its effect on vegetation and soils, desertification changes the absorption and release of associated greenhouse gases (GHGs). Vegetation loss and drying of surface cover due to desertification increases the frequency of dust storms (*high confidence*). Arid ecosystems could be an important global carbon sink depending on soil water availability (*medium evidence, high agreement*). {3.4.3, 3.5.1, 3.6.2}

Site-specific technological solutions, based both on new scientific innovations and indigenous and local knowledge (ILK), are available to avoid, reduce and reverse desertification, simultaneously contributing to climate change mitigation and adaptation (***high confidence***). SLM practices in drylands increase agricultural productivity and contribute to climate change adaptation and mitigation (*high confidence*). Integrated crop, soil and water management measures can be employed to reduce soil degradation and increase the resilience of agricultural production systems to the impacts of climate change (*high confidence*). These measures include crop diversification and adoption of drought-tolerant crops, reduced tillage, adoption of improved irrigation techniques (e.g. drip irrigation) and moisture conservation methods (e.g. rainwater harvesting using indigenous and local practices), and maintaining vegetation and mulch cover. Conservation agriculture increases the capacity of agricultural households to adapt to climate change (*high confidence*) and can lead to increases in soil organic carbon over time, with quantitative estimates of the rates of carbon sequestration in drylands following changes in agricultural practices ranging between 0.04-0.4 t ha^{-1}(*medium confidence*). Rangeland management systems based on sustainable grazing and re-vegetation increase rangeland productivity and the flow of ecosystem services (*high confidence*). The combined use of salt-tolerant crops, improved irrigation practices, chemical remediation measures and appropriate mulch and compost is effective in reducing the impact of secondary salinisation (*medium confidence*). Application of sand dune stabilisation techniques contributes to reducing sand and dust storms (*high confidence*). Agroforestry practices and shelterbelts help reduce soil erosion and sequester carbon. Afforestation programmes aimed at creating windbreaks in the form of "green walls" and "green dams" can help stabilise and reduce dust storms, avert wind erosion, and serve as carbon sinks, particularly when done with locally adapted tree species *(high confidence*). {3.5.2, 3.7.1, 3.8.2}

Investments into SLM, land restoration and rehabilitation in dryland areas have positive economic returns (***high confidence***). Each USD invested into land restoration can have social returns of about 3–6 USD over a 30-year period. Most SLM practices can become financially profitable within three to 10 years (*medium evidence*, *high agreement*). Despite their benefits in addressing desertification, mitigating and adapting to climate change, and increasing food and economic security, many SLM practices are not widely adopted due to insecure land tenure, lack of access to credit and agricultural advisory services, and insufficient incentives for private land users *(robust evidence*, *high agreement*). {3.7.3}

Indigenous and local knowledge (ILK) often contribute to enhancing resilience against climate change and combating desertification (***medium confidence***). Dryland populations have developed traditional agroecological practices which are well adapted to resource-sparse dryland environments. However, there is *robust evidence* documenting losses of traditional agroecological knowledge. Traditional agroecological practices are also increasingly unable to cope with growing demand for food. Combined use of ILK and new SLM technologies can contribute to raising the resilience to the challenges of climate change and desertification (*high confidence*). {3.2.3, 3.7.1, 3.7.2}

Policy frameworks promoting the adoption of SLM solutions contribute to addressing desertification as well as mitigating and adapting to climate change, with co-benefits for poverty reduction and food security among dryland populations (***high confidence***). **Implementation of Land Degradation Neutrality policies allows to avoid, reduce and reverse desertification, thus, contributing to climate change adaptation and mitigation (*high confidence*).** Strengthening land tenure security is a major factor contributing to the adoption of soil conservation measures in croplands (*high confidence*). On-farm and off-farm livelihood diversification strategies increase the resilience of rural households against desertification and extreme weather events, such as droughts (*high confidence*). Strengthening collective action is important for addressing causes and impacts of desertification, and for adapting to climate change (*medium confidence*). A greater emphasis on understanding gender-specific differences over land use and land management practices can help make land restoration projects more successful (*medium confidence*). Improved access to markets raises agricultural profitability and motivates investment into climate change adaptation and SLM (*medium confidence*). Payments for ecosystem services give additional incentives to land users to adopt SLM practices (*medium confidence*). Expanding access to rural advisory services increases the knowledge on SLM and facilitates their wider adoption (*medium confidence*). Transition to modern renewable energy sources can contribute to reducing desertification and mitigating climate change through decreasing the use of fuelwood and crop residues for energy (*medium confidence*). Policy responses to droughts based on pro-active drought preparedness and drought risk mitigation are more efficient in limiting drought-caused damages than reactive drought relief efforts (*high confidence*). {3.5.2, 3.7.2, 3.7.3, Cross-Chapter Box 5: Policy Responses to Drought in Chapter 3}

The knowledge on limits to adaptation to combined effects of climate change and desertification is insufficient. However, the potential for residual risks and maladaptive outcomes is high (*high confidence*). Empirical evidence on the limits to adaptation in dryland areas is limited, potential limits to adaptation include losses of land productivity due to irreversible forms of desertification. Residual risks can emerge from the inability of SLM measures to fully compensate for yield losses due to climate change impacts, as well as foregone reductions in ecosystem services due to soil fertility loss even when applying SLM measures could revert land to initial productivity after some time. Some activities favouring agricultural intensification in dryland areas can become maladaptive due to their negative impacts on the environment (*medium confidence*) {3.7.4}.

Improving capacities, providing higher access to climate services, including local level early warning systems, and expanding the use of remote sensing technologies are high return investments for enabling effective adaptation and mitigation responses that help address desertification (***high confidence***). Reliable and timely climate services, relevant to desertification, can aid the development of appropriate adaptation and mitigation options reducing the impact of desertification on human and natural systems (*high confidence*), with quantitative estimates pointing that every USD invested in strengthening hydro-meteorological and early warning services in developing countries can yield between 4 to 35 USD (*low confidence)*. Knowledge and flow of knowledge on desertification is currently fragmented. Improved knowledge and data exchange and sharing will increase the effectiveness of efforts to achieve Land Degradation Neutrality (*high confidence*). Expanded use of remotely sensed information for data collection helps in measuring progress towards achieving Land Degradation Neutrality (*low evidence, high agreement*). {3.3.1, 3.7.2, 3.7.3, Cross-Chapter Box 5: Policy Responses to Drought in Chapter 3}

TS.4. Land Degradation

Land degradation affects people and ecosystems throughout the planet and is both affected by climate change and contributes to it. In this report, 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.* Forest degradation is land degradation which occurs in forest land. Deforestation is the conversion of forest to non-forest land and can result in land degradation. {4.2.3}

Land degradation adversely affects people's livelihoods *(very high confidence)* and occurs over a quarter of the Earth's ice-free land area *(medium confidence)*. The majority of the 1.3 to 3.2 billion affected people *(low confidence)* are living in poverty in developing countries *(medium confidence)*. Land use changes and unsustainable land management are direct human causes of land degradation (*very high confidence*), with agriculture being a dominant sector driving degradation (*very high confidence*). Soil loss from conventionally tilled land exceeds the rate of soil formation by >2 orders of magnitude (*medium confidence*). Land degradation affects humans in multiple ways, interacting with social, political, cultural and economic aspects, including markets, technology, inequality and demographic change (*very high confidence*). Land degradation impacts extend beyond the land surface itself, affecting marine and freshwater systems, as well as people and ecosystems far away from the local sites of degradation (*very high confidence*). {4.2.6, 4.3.1, 4.3.3, 4.4, 4.7.1, 4.8, Table 4.1}

Climate change exacerbates the rate and magnitude of several ongoing land degradation processes and introduces new degradation patterns (*high confidence*). Human-induced global warming has already caused observed changes in two drivers of land degradation: increased frequency, intensity and/or amount of heavy precipitation (*medium confidence*), and increased heat stress *(high* *confidence*). Global warming beyond that of present-day will further exacerbate ongoing land degradation processes through increasing floods (*medium confidence*), drought frequency and severity (*medium confidence*), intensified cyclones (*medium confidence*), and sea-level rise (*very high confidence*), with outcomes being modulated by land management (*very high confidence*). Permafrost thawing due to warming (*high confidence*), and coastal erosion due to sea level rise and impacts of changing storm paths (*low confidence*), are examples of land degradation affecting places in which it has not typically been a problem. Erosion of coastal areas because of sea level rise will increase worldwide (*high confidence*). In cyclone prone areas the combination of sea level rise and more intense cyclones will cause land degradation with serious consequences for people and livelihoods (*very high confidence*). {4.3.1, 4.3.2, 4.3.3, 4.5.1, 4.5.2, 4.10.6, Table 4.1}

Land degradation and climate change, both individually and in combination, have profound implications for natural resource-based livelihood systems and societal groups (*high confidence*). The number of people whose livelihood depends on degraded lands has been estimated to ~1.5 billion worldwide (*very low confidence*). People in degraded areas who directly depend on natural resources for subsistence, food security and income, including women and youth with limited adaptation options, are especially vulnerable to land degradation and climate change (*high confidence*). Land degradation reduces land productivity and increases the work load of managing the land, affecting women disproportionally in some regions. Land degradation and climate change act as threat multipliers for already precarious livelihoods (*very high confidence*), leaving them highly sensitive to extreme climatic events, with consequences such as poverty and food insecurity (*high confidence*), and in some cases migration, conflict and loss of cultural heritage (*low confidence*). Changes in vegetation cover and distribution due to climate change increase risks of land degradation in some areas (*medium confidence*). Climate change will have detrimental effects on livelihoods, habitats, and infrastructure through increased rates of land degradation (*high confidence*) and from new degradation patterns (*low evidence, high agreement*). {4.2.6, 4.3.1, 4.8}

Land degradation is a driver of climate change through emission of greenhouse gases and reduced rates of carbon uptake *(very high confidence*). Since 1990, globally the forest area has decreased by 3% (*low confidence*) with net decreases in the tropics and net increases outside the tropics (*high confidence*). Lower carbon density in re-growing forests compared to carbon stocks before deforestation results in net emissions from land use change (*very high confidence*). Forest management that reduces carbon stocks of forest land also leads to emissions, but global estimates of these emissions are uncertain. Cropland soils have lost 20-60% of their organic carbon content prior to cultivation, and soils under conventional agriculture continue to be a source of greenhouse gases (*medium confidence*). Of the land degradation processes, deforestation, increasing wildfires, degradation of peat soils, and permafrost thawing contribute most to climate change through the release of greenhouse gases and the reduction in land carbon sinks following deforestation (*high confidence*). Agricultural practices also emit non-CO_2 greenhouse gases from soils and these emissions are exacerbated by climate change (*medium confidence*). Conversion of primary to managed forests, illegal logging and unsustainable forest management result in greenhouse gas emissions (*very high confidence*) and can have additional physical effects on the regional climate including those arising from albedo shifts (*medium confidence*). These interactions call for more integrative climate impact assessments. {4.3.2, 4.4, 4.6.4, 4.7}

Large-scale implementation of dedicated biomass production for bioenergy increases competition for land with potentially serious consequences for food security and land degradation *(high confidence)*. Increasing the extent and intensity of biomass production through e.g. fertiliser additions, irrigation or monoculture energy plantations can result in local land degradation. Poorly implemented intensification of land management contributes to land degradation (e.g., salinisation from irrigation) and disrupted livelihoods (*high confidence*). In areas where afforestation and reforestation occur on previously degraded lands, opportunities exist to restore and rehabilitate lands with potentially significant co-benefits (*high confidence*) that depend on whether restoration involves natural or plantation forests. The total area of degraded lands has been estimated at 1-6 Mkm^2 (*very low confidence*). The extent of degraded and marginal lands suitable for dedicated biomass production is highly uncertain and cannot be established without due consideration of current land use and land tenure. Increasing the area of dedicated energy crops can lead to land degradation elsewhere through indirect land use change (*medium confidence*). Impacts of energy crops can be reduced through strategic integration with agricultural and forestry systems (*high confidence*) but the total quantity of biomass that can be produced through synergistic production systems is unknown. {4.2.6, 4.5.2, 4.6, 4.8.1, 4.9.1, 4.9.3, 4.9.4, 4.10.3}

Reducing unsustainable use of traditional biomass reduces land degradation and emissions of CO_2, while providing social and economic co-benefits (*very high confidence*). Traditional biomass in the form of fuelwood, charcoal and agricultural residues remains a primary source of energy for more than one-third of the global population leading to unsustainable use of biomass resources and forest degradation and contributing around 2% of global greenhouse gas (GHG) emissions (*low confidence*). Enhanced forest protection, improved forest and agricultural management, fuel-switching and adoption of efficient cooking and heating appliances can promote more sustainable biomass use and reduce land degradation, with co-benefits of reduced GHG emissions, improved human health, and reduced workload especially for women and youth (*very high confidence*). {4.2.6, 4.6.4}

Land degradation can be avoided, reduced or reversed by implementing sustainable land management, restoration and rehabilitation practices that simultaneously provide many co-benefits, including adaptation to and mitigation of climate change *(high confidence)*. Sustainable land management is a comprehensive array of technologies and enabling conditions, which have proven to address land degradation at multiple landscape scales, from local farms *(very high confidence)* to entire watersheds *(medium confidence)*. Sustainable forest management can prevent deforestation, maintain and enhance carbon sinks and can contribute towards greenhouse gas emissions reduction goals. Sustainable forest management generates socio-economic benefits, provides fiber, timber and biomass to meet society's growing needs. While sustainable forest management sustains high carbon sinks, the conversion from primary forests to sustainably managed forests can result in carbon emission during the transition and can result in loss of biodiversity *(high confidence)*. Conversely, in areas of degraded forests, sustainable forest management can increase carbon stocks and biodiversity *(medium confidence)*. Carbon storage in long-lived wood products and reductions of emissions from use of wood products to substitute for emissions-intensive materials also contribute to mitigation objectives (Figure TS. 8). {4.9, 4.10, Table 4.2}

Interaction of human and climate drivers can exacerbate desertification and land degradation Climate change exacerbates the rate and magnitude of several ongoing land degradation and desertification processes. Human drivers of land degradation and desertification include expanding agriculture, agricultural practices and forest management. In turn land degradation and desertification are also drivers of climate change through the emission of greenhouse gases, reduced rates of carbon uptake and reduced capacity of ecosystems to act as carbon sinks into the future.

Human driver	Climate driver
Grazing pressure	Warming trend
Agriculture practices	Extreme temperatures
Expansion of agriculture	Drying trend
Forest clearing	Extreme rainfall
Wood fuel	Shifting rains
	Intensifying cyclones
	Sea level rise

Issue/syndrome	Impact on climate change	Human driver	Climate driver	Land management options
Erosion of agricultural soils	Emission: CO_2, N_2O			Increase soil organic matter, no till, perennial crops, erosion control, agroforestry, dietary change
Deforestation	Emission of CO_2			Forest protection, sustainable forest management and dietary change
Forest degradation	Emission of CO_2 Reduced carbon sink			Forest protection, sustainable forest management
Overgrazing	Emission: CO_2, CH_4 Increasing albedo			Controlled grazing, rangeland management
Firewood and charcoal production	Emission: CO_2, CH_4 Increasing albedo			Clean cooking (health co-benefits, particularly for women and children)
Increasing fire frequency and intensity	Emission: CO_2, CH_4, N_2O Emission: aerosols, increasing albedo			Fuel management, fire management
Degradation of tropical peat soils	Emission: CO_2, CH_4			Peatland restoration, erosion control, regulating the use of peat soils
Thawing of perma-frost	Emission: CO_2, CH_4			None
Coastal erosion	Emission: CO_2, CH_4			Wetland and coastal restoration, mangrove conservation, long term land use planning
Sand and dust storms, wind erosion	Emission: aerosols			Vegetation management, afforestation, windbreaks
Bush encroachment	Capturing: CO_2, Decreasing albedo			Grazing land management, fire management

Figure TS. 8 Interaction of human and climate drivers can exacerbate desertification and land degradation. Figure shows key desertification and land degradation issues, how they impact climate change, and the key drivers, with potential solutions.

Lack of action to address land degradation will increase emissions and reduce carbon sinks and is inconsistent with the emission reductions required to limit global warming to 1.5°C or 2°C. (*high confidence*). Better management of soils can offset 5–20% of current global anthropogenic GHG emissions (*medium confidence*). Measures to avoid, reduce and reverse land degradation are available but economic, political, institutional, legal and socio-cultural barriers, including lack of access to resources and knowledge, restrict their uptake (*very high confidence*). Proven measures that facilitate implementation of practices that avoid, reduce, or reverse land degradation include tenure reform, tax incentives, payments for ecosystem services, participatory integrated land use planning, farmer networks and rural advisory services. Delayed action increases the costs of addressing land degradation, and can lead to irreversible biophysical and human outcomes (*high confidence*). Early actions can generate both site specific and immediate benefits to communities affected by land degradation, and contribute to long-term global benefits through climate change mitigation (*high confidence*) (Figure TS. 9). {4.2.5, 4.2.6, 4.8.1, 4.9, Table 4.2}

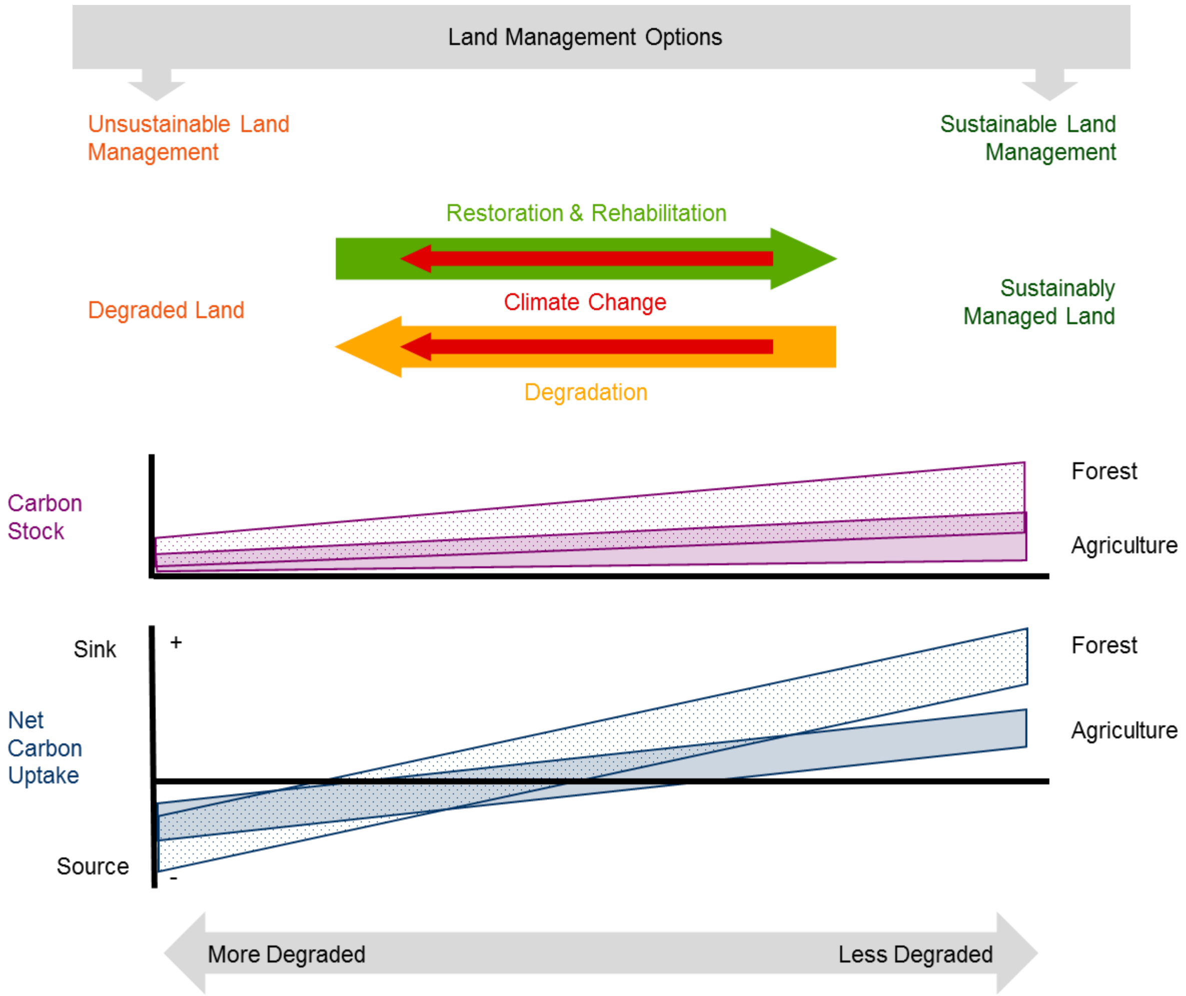

Figure TS. 9 Conceptual figure illustrating that climate change impacts interact with land management to determine sustainable or degraded outcome. Climate change can exacerbate many degradation processes (Table 4.1) and introduce novel ones (e.g., permafrost thawing or biome shifts), hence management needs to respond to climate impacts in order to avoid, reduce or reverse degradation. The types and intensity of human land use and climate change impacts on lands affect their carbon stocks and their ability to operate as carbon sinks. In managed agricultural lands, degradation typically results in reductions of soil organic carbon stocks, which also adversely affects land productivity and carbon sinks. In forest land, reduction in biomass carbon stocks alone is not necessarily an indication of a reduction in carbon sinks. Sustainably managed forest landscapes can have a lower biomass carbon density but the younger forests can have a higher growth rate, and therefore contribute stronger carbon sinks, than older forests. Ranges of carbon sinks in forest and agricultural lands are overlapping. In some cases, climate change impacts may result in increased productivity and carbon stocks, at least in the short term.

Even with adequate implementation of measures to avoid, reduce and reverse land degradation there will be residual degradation in some situations *(high confidence)*. Limits to adaptation are dynamic, site specific and are determined through the interaction of biophysical changes with social and institutional conditions. Exceeding the limits of adaptation will trigger escalating losses or result in undesirable changes, such as forced migration, conflicts, or poverty. Examples of potential limits to adaptation due to climate change induced land degradation are coastal erosion where land disappears, collapsing infrastructure and livelihoods due to thawing of permafrost, and extreme forms of soil erosion. {4.8, 4.9.5, 4.9.6, 4.10.6, 4.10.7, 4.10.8}

Land degradation is a serious and widespread problem, yet key uncertainties remain concerning its extent, severity, and linkages to climate change *(very high confidence).* Despite the difficulties of objectively measuring the extent and severity of land degradation given its complex and value-based characteristics, land degradation represents, like climate change, one of the biggest and most urgent challenges for humanity (*very high confidence*). The current global extent, severity and rates of land degradation are not well quantified. There is no single method by which land degradation can be measured objectively and consistently over large areas because it is such a complex and value laden concept (*very high confidence*). However, many scientific and locally-based approaches, including the use of indigenous and local knowledge, exist that can assess different aspects of land degradation or provide proxies. Remote sensing, corroborated by other data, can generate geographically explicit and globally consistent data that can be used as proxies over relevant time scales (several decades). Few studies have specifically addressed the impacts of proposed land-based negative emission technologies on land degradation. Much research has tried to understand how livelihoods and ecosystems are affected by a particular stressor, for example drought, heat stress, or water logging. Important knowledge gaps remain in understanding how plants, habitats and ecosystems are affected by the cumulative and interacting impacts of several stressors, including potential new stressors resulting from large-scale implementation of negative emission technologies. {4.1.1}

TS.5. Food Security

The current food system (production, transport, processing, packaging, storage, retail, consumption, loss and waste) feeds the great majority of world population and supports the livelihoods of ca. 200 million people. Since 1961, food supply per capita has increased more than 30%, accompanied by greater use of nitrogen fertilisers (increase of about 800%) and water resources for irrigation (increase of more than 100%). However, an estimated 821 million people are currently undernourished, 151 million children under 5 are stunted, 613 million women and girls aged 15 to 49 suffer from iron deficiency, and 2 billion adults are overweight or obese. The food system is under pressure from non-climate stressors (e.g., population and income growth, demand for animal-sourced products), and from climate change. These climate and non-climate stresses are impacting the four pillars of food security (availability, access, utilisation, and stability) (Figure TS. 10). {5.1.1, 5.1.2}

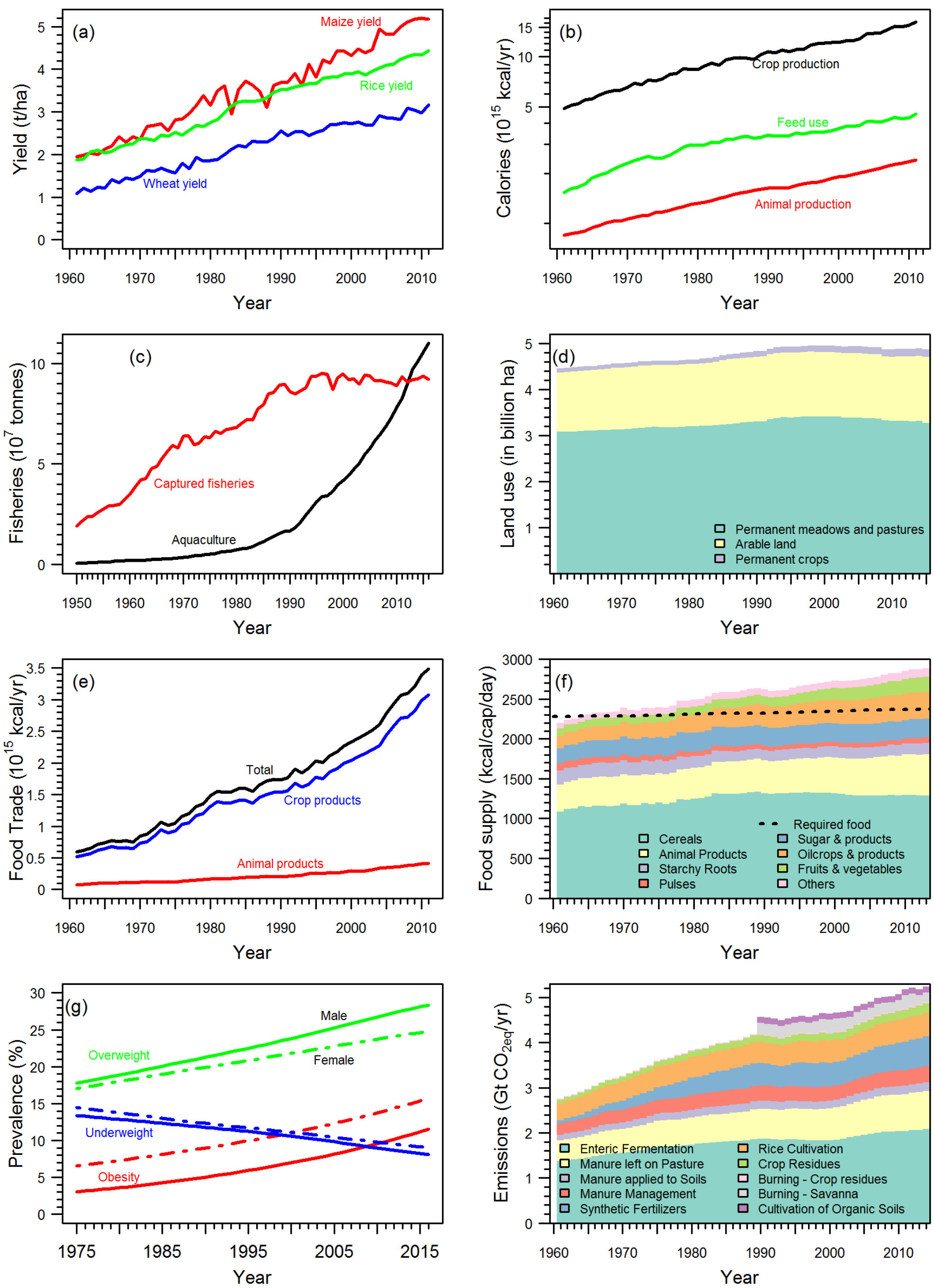

Figure TS. 10 Global trends in (a) yields of maize, rice, and wheat (FAOSTAT 2018) – the top three crops grown in the world; (b) production of crop and animal calories and use of crop calories as livestock feed (FAOSTAT 2018); (c) production from marine and aquaculture fisheries (FishStat 2019); (d) land used for agriculture (FAOSTAT 2018); (e) food trade in calories (FAOSTAT 2018); (f) food supply and required food (i.e., based on human energy requirement for medium physical activities) from 1961–2012 (FAO 2018b; Hiç et al. 2016); (g) prevalence of overweight, obesity and underweight from 1975–2015 (Abarca-Gómez et al. 2017); and (h) GHG emissions for the agriculture sector, excluding land use change (FAOSTAT 2018). For figures (b) and (e), data provided in mass units were converted into calories using nutritive factors (FAO 2001b). Data on emissions due to burning of savanna and cultivation of organic soils is provided only after 1990 (FAOSTAT 2018).

Observed climate change is already affecting food security through increasing temperatures, changing precipitation patterns, and greater frequency of some extreme events *(high confidence)*. Increasing temperatures are affecting agricultural productivity in higher latitudes, raising yields of some crops (maize, cotton, wheat, sugar beets), while yields of others (maize, wheat, barley) are declining in lower-latitude regions. Warming compounded by drying has caused yield declines in parts of Southern Europe. Based on indigenous and local knowledge, climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America (Figure TS. 11). {5.2.2}

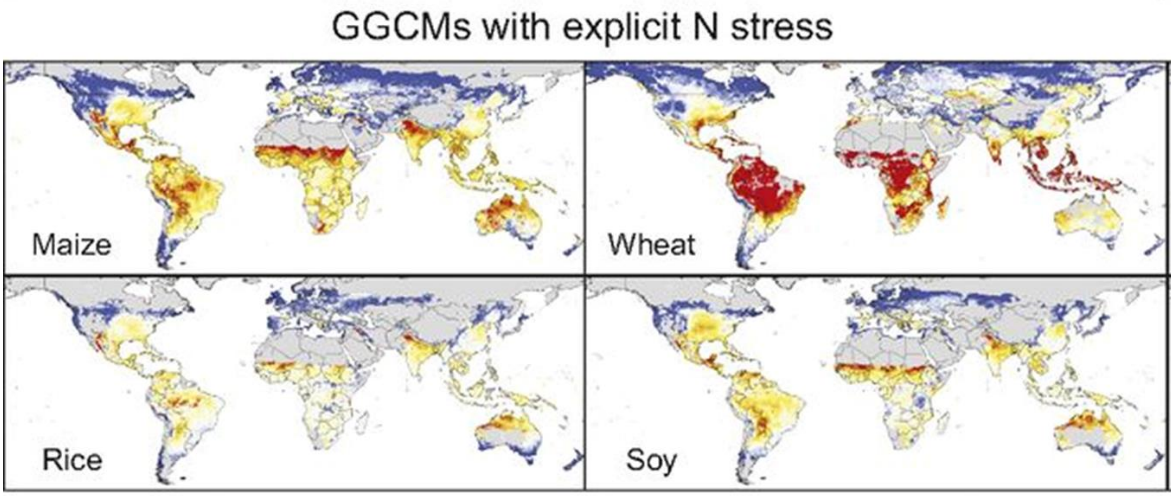

Figure TS. 11 Median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects and explicit nitrogen stress over five GCMs x four Global Gridded Crop Models (GGCMs) for rainfed maize, wheat, rice, and soy (20 ensemble members from EPIC, GEPIC, pDSSAT, and PEGASUS; except for rice which has 15). Gray areas indicate historical areas with little to no yield capacity. All models use a 0.5° grid, but there are differences in grid cells simulated to represent agricultural land. While some models simulated all land areas, others simulated only potential suitable cropland area according to evolving climatic conditions; others utilised historical harvested areas in 2000 according to various data sources (Rosenzweig et al. 2014).

Food security will be increasingly affected by projected future climate change *(high confidence)*. Across SSPs 1, 2, and 3, global crop and economic models projected a 1-29% cereal price increase in 2050 due to climate change (RCP 6.0), which would impact consumers globally through higher food prices; regional effects will vary *(high confidence)*. Low-income consumers are particularly at risk, with models projecting increases of 1-183 million additional people at risk of hunger across the SSPs compared to a no climate change scenario *(high confidence)*. While increased CO_2 is projected to be beneficial for crop productivity at lower temperature increases, it is projected to lower nutritional quality *(high confidence)* (e.g., wheat grown at 546-586 ppm CO_2 has 5.9–12.7% less protein, 3.7–6.5% less zinc, and 5.2–7.5% less iron). Distributions of pests and diseases will change, affecting production negatively in many regions *(high confidence)*. Given increasing extreme events and interconnectedness, risks of food system disruptions are growing *(high confidence)*. {5.2.3, 5.2.4}

Vulnerability of pastoral systems to climate change is very high (*high confidence*). Pastoralism is practiced in more than 75% of countries by between 200 and 500 million people, including nomadic communities, transhumant herders, and agro-pastoralists. Impacts in pastoral systems include lower pasture and animal productivity, damaged reproductive function, and biodiversity loss. Pastoral system vulnerability is exacerbated by non-climate factors (land tenure, sedentarisation, changes in traditional institutions, invasive species, lack of markets, and conflicts). {5.2.2}

Fruit and vegetable production, a key component of healthy diets, is also vulnerable to climate change *(medium evidence, high agreement)*. Declines in yields and crop suitability are projected under higher temperatures, especially in tropical and semi-tropical regions. Heat stress reduces fruit set and speeds up development of annual vegetables, resulting in yield losses, impaired product quality, and increasing food loss and waste. Longer growing seasons enable a greater number of plantings to be cultivated and can contribute to greater annual yields. However, some fruits and vegetables need a period of cold accumulation to produce a viable harvest, and warmer winters may constitute a risk. {5.2.2}

Food security and climate change have strong gender and equity dimensions (*high confidence*). Worldwide, women play a key role in food security, although regional differences exist. Climate change impacts vary among diverse social groups depending on age, ethnicity, gender, wealth, and class. Climate extremes have immediate and long-term impacts on livelihoods of poor and vulnerable communities, contributing to greater risks of food insecurity that can be a stress multiplier for internal and external migration *(medium confidence).* {5.2.6} Empowering women and rights-based approaches to decision-making can create synergies among household food security, adaptation, and mitigation. {5.6.4}

Many practices can be optimised and scaled up to advance adaptation throughout the food system *(high confidence)*. Supply-side options include increased soil organic matter and erosion control, improved cropland, livestock, and grazing land management, and genetic improvements for tolerance to heat and drought. Diversification in the food system (e.g., implementation of integrated production systems, broad-based genetic resources, and heterogeneous diets) is a key strategy to reduce risks (*medium confidence*). Demand-side adaptation, such as adoption of healthy and sustainable diets, in conjunction with reduction in food loss and waste, can contribute to adaptation through reduction in additional land area needed for food production and associated food system vulnerabilities. Indigenous and local knowledge can contribute to enhancing food system resilience *(high confidence)*. {5.3, 5.6.3 Cross-Chapter Box 6: Agricultural Intensification in Chapter 5}.

Ca. 25-30% of total GHG emissions are attributable to the food system. These are from agriculture and land use, storage, transport, packaging, processing, retail, and consumption *(medium confidence)*. This estimate includes emissions of 10–12% from crop and livestock activities within the farm gate and 8-10% from land use and land use change including deforestation and peatland degradation *(high confidence)*; 5–10% is from supply chain activities *(medium confidence)*. This estimate includes GHG emissions from food loss and waste. Within the food system, during the period 2007-2016, the major sources of emissions from the supply side were agricultural production, with crop and livestock activities within the farm gate generating respectively 142 ± 43 Tg CH_4 yr^{-1} *(high confidence)* and 8.3 ± 2.3 Tg N_2O yr^{-1} *(high confidence)*, and CO_2 emissions linked to relevant land use change dynamics such as deforestation and peatland degradation, generating 4.8 ± 2.4 Gt CO_2 yr^{-1}. Using 100-year GWP values (no climate feedback) from the IPCC AR5, this implies that total GHG emissions from agriculture were 6.2 ± 1.9 Gt CO_2eq yr^{-1}, increasing to 11.0 ± 3.1 Gt CO_2eq yr^{-1} including relevant land use. Without intervention, these are likely to increase by about 30%–40% by 2050, due to increasing demand based on population and income growth and dietary change *(high confidence)*. {5.4}

Supply-side practices can contribute to climate change mitigation by reducing crop and livestock emissions, sequestering carbon in soils and biomass, and by decreasing emissions intensity within sustainable production systems *(high confidence)*. Total mitigation potential of crop and livestock activities is estimated as 1.5–4.0 GtCO_2-eq yr^{-1} by 2030 at prices ranging from 20-100 USD/tCO_2eq *(high confidence)*. Options with large potential for GHG mitigation in cropping systems include soil carbon sequestration (at decreasing rates over time), reductions in N_2O emissions from fertilisers, reductions in CH_4 emissions from paddy rice, and bridging of yield gaps. Options with large potential for mitigation in livestock systems include better grazing land management, with increased net primary production and soil carbon stocks, improved manure management, and higher-quality feed. Reductions in GHG emissions intensity (emissions per unit product) from livestock can support reductions in absolute emissions, provided appropriate governance to limit total production is implemented at the same time (*medium confidence*). {5.5.1}

Consumption of healthy and sustainable diets presents major opportunities for reducing GHG emissions from food systems and improving health outcomes *(high confidence)*. Examples of healthy and sustainable diets are high in coarse grains, pulses, fruits and vegetables, and nuts and seeds; low in energy-intensive animal-sourced and discretionary foods (such as sugary beverages); and with a carbohydrate threshold. Total mitigation potential of dietary changes is estimated as 1.8-3.4 $GtCO_2eq$ yr^{-1} by 2050 at prices ranging from 20-100 USD/tCO_2 *(medium confidence)*. This estimate includes reductions in emissions from livestock and soil carbon sequestration on spared land, but co-benefits with health are not taken into account. Mitigation potential of dietary change may be higher, but achievement of this potential at broad scales depends on consumer choices and dietary preferences that are guided by social, cultural, environmental, and traditional factors, as well as income growth. Meat analogues such as imitation meat (from plant products), cultured meat, and insects may help in the transition to more healthy and sustainable diets, although their carbon footprints and acceptability are uncertain. {5.5.2, 5.6.5}

Reduction of food loss and waste could lower GHG emissions and improve food security *(medium confidence)*. Combined food loss and waste amount to a third of global food production *(high confidence)*. During 2010-2016, global food loss and waste equalled 8–10% of total GHG emissions from food systems *(medium confidence)*; and cost about USD 1 trillion per year (2012 prices) *(low confidence)*. Technical options for reduction of food loss and waste include improved harvesting techniques, on-farm storage, infrastructure, and packaging. Causes of food loss (e.g., lack of refrigeration) and waste (e.g., behaviour) differ substantially in developed and developing countries, as well as across regions *(robust evidence, medium agreement)*. {5.5.2}

Agriculture and the food system are key to global climate change responses. Combining supply-side actions such as efficient production, transport, and processing with demand-side interventions such as modification of food choices, and reduction of food loss and waste, reduces GHG emissions and enhances food system resilience (*high confidence*). Such combined measures can enable the implementation of large-scale land-based adaptation and mitigation strategies without threatening food security from increased competition for land for food production and higher food prices. Without combined food system measures in farm management, supply chains, and demand, adverse effects would include increased number of malnourished people and impacts on smallholder farmers (*medium evidence, high agreement*). Just transitions are needed to address these effects. (Figure TS. 12). {5.5, 5.6, 5.7}

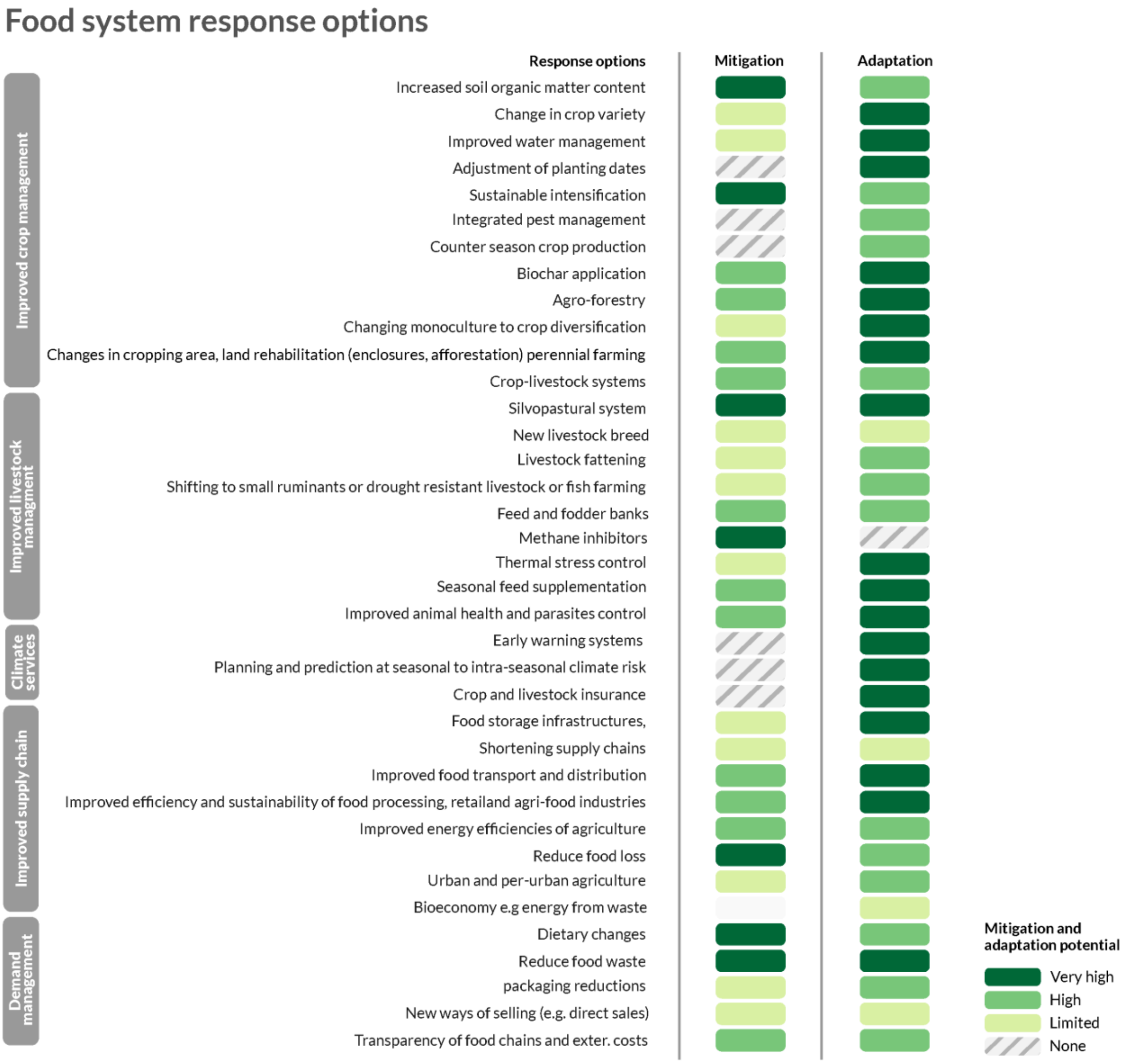

Figure TS. 12 Response options related to food system and their potential impacts on mitigation and adaptation. Many response options offer significant potential for both mitigation and adaptation (see also SPM Figure 3 and Chapter 6 for details).

For adaptation and mitigation throughout the food system, enabling conditions need to be created through policies, markets, institutions, and governance (high confidence). For adaptation, resilience to increasing extreme events can be accomplished through risk sharing and transfer mechanisms such as insurance markets and index-based weather insurance (high confidence). Public health policies to improve nutrition – such as school procurement, health insurance incentives, and awareness-raising campaigns – can potentially change demand, reduce health-care costs, and contribute to lower GHG emissions (limited evidence, high agreement). Without inclusion of comprehensive food system responses in broader climate change policies, the mitigation and adaptation potentials assessed in this chapter will not be realised and food security will be jeopardised (high confidence). {5.7}

TS.6. Interlinkages between Desertification, Land Degradation, Food Security and GHG fluxes: synergies, trade-offs and Integrated Response Options

The land challenges, in the context of this report, are climate change mitigation, adaptation, desertification, land degradation, and food security. The chapter also discusses implications for Nature's Contributions to People (NCP), including biodiversity and water, and sustainable development, by assessing intersections with the Sustainable Development Goals (SDGs). The chapter assesses response options that could be used to address these challenges. These response options were derived from the previous chapters and fall into three broad categories (land management, value chain, and risk management).

The land challenges faced today vary across regions; climate change will increase challenges in the future, while socioeconomic development could either increase or decrease challenges (*high confidence*). Increases in biophysical impacts from climate change can worsen desertification, land degradation, and food insecurity (*high confidence*). Additional pressures from socioeconomic development could further exacerbate these challenges; however, the effects are scenario dependent. Scenarios with increases in income and reduced pressures on land can lead to reductions in food insecurity; however, all assessed scenarios result in increases in water demand and water scarcity (*medium confidence*). {6.2}

The applicability and efficacy of response options are region and context specific; while many value chain and risk management options are potentially broadly applicable, many land management options are applicable on less than 50% of the ice-free land surface (*high confidence*). Response options are limited by land type, bioclimatic region, or local food system context (*high confidence*). Some response options produce adverse side-effects only in certain regions or contexts; for example, response options that use freshwater may have no adverse side effects in regions where water is plentiful, but large adverse side effects in regions where water is scarce (*high confidence*). Response options with biophysical climate effects (e.g., afforestation, reforestation) may have different effects on local climate depending on where they are implemented (*medium confidence*). Regions with more challenges have fewer response options available for implementation (*medium confidence*). {6.2, 6.3, 6.4, 6.5}

Eight options deliver medium to large benefits for all five land challenges (*high confidence*). The options with medium to large benefits for all challenges are increased food productivity, improved forest management, reduced deforestation and degradation, increased soil organic carbon content, enhanced mineral weathering, dietary change, reduced post-harvest losses, and reduced food waste (*high confidence*). {6.4, 6.5}

Eight options have large mitigation potential (>3 $GtCO_2e\ yr^{-1}$) without adverse side-effects for other challenges (*high confidence*). These are increased food productivity, agroforestry, improved livestock management, reduced deforestation and degradation, increased soil organic carbon content, dietary change, reduced post-harvest losses and reduced food waste (*high confidence*). Other options: improved cropland management, improved grazing land management, integrated water management, forest management, fire management, improved food processing and retailing, and improved energy use in food systems, have moderate mitigation potential, without adverse side-effects for other challenges (*high confidence*). {6.4.6}

Sixteen response options have large adaptation potential (>25 million people benefit), without adverse side-effects on other land challenges (*high confidence*). These are increased food productivity, improved cropland management, agroforestry, agricultural diversification, improved forest management, increased soil organic carbon content, reduced landslides and natural hazards, restoration and reduced conversion of coastal wetlands, reduced post-harvest losses, sustainable sourcing, management of supply chains, improved food processing and retailing, improved energy use in food systems, livelihood diversification, use of local seeds, and disaster risk management (*high confidence*). Some options (such as enhanced urban food systems or management of urban sprawl) may not provide large global benefits but may have significant positive local effects without adverse effects (*high confidence*) (Figure TS. 13). {6.4, 6.5; Figure SPM3}

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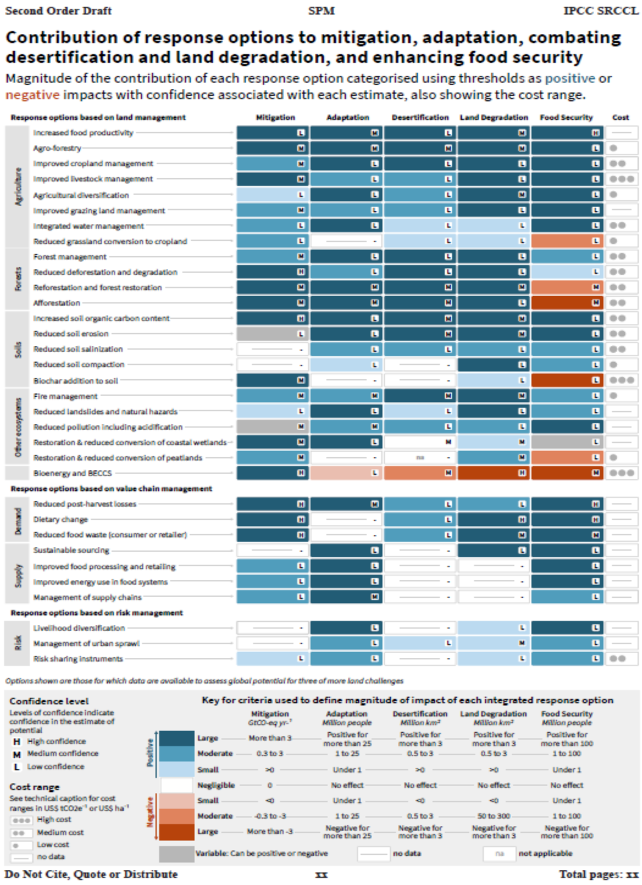

[SPM3]

Figure TS. 13 Contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security. Magnitude of potential: All numbers are for global scale of technical potential. For mitigation, the threshold is set at around the level of large single mitigation measure (~3 $GtCO_2$-eq yr^{-1}) (Pacala and Socolow 2004), with a combined threshold to meet 100 $GtCO_2$ in 2100, to go from baseline to 2˚C (Clarke and Jiang 2014a). For adaptation, numbers are set relative to the about 5 million lives lost per year attributable to climate change and the 100 million lives predicted to be lost between 2010 and 2030 (DARA 2012) with the largest category representing 25% of this total. For desertification and land degradation, categories are set relative to the 10-60 million km^2 of currently degraded land (Gibbs and Salmon 2015) with the largest category representing 30% of the lower estimate. For food security, categories are set relative to the about 800 million people currently undernourished (HLPE 2017) with the largest category representing around 12.5% of this total. Potentials assume large land areas required for large-scale Afforestation and Reforestation, and for feedstock production for large-scale Bioenergy and BECCS and for Biochar. Increased food production assumes that it is achieved through sustainable intensification rather than through application of additional external inputs such as mineral fertilisers and other agrochemicals. Levels of confidence: Levels of confidence indicate confidence in the estimate of potential being in the high, medium or low categories for each land challenge (mitigation, adaptation, combating desertification and land degradation, and enhancing food security) shown in the magnitude of contribution key. High confidence means that there is a high level of agreement and evidence in the literature to support the categorisation as high, medium or low magnitude. Low confidence denotes that the categorisation of magnitude is based on few studies. Medium confidence reflects medium evidence and agreement in the magnitude of response. Cost ranges: One coin indicates low cost (<\$10 tCO_2-eq^{-1} or <\$20 ha^{-1}), two coins indicate medium cost (\$10-\$100 tCO_2-eq^{-1} or \$20-\$100 ha^{-1}), and three coins indicate high cost (>\$100 tCO_2-eq^{-1} or \$200 ha^{-1}). The cost thresholds in \$t/CO_2-eq are from Griscom et al. (2017); thresholds in \$ ha^{-1} are chosen to be comparable, but precise conversions will depend on the response option. Supporting evidence: Supporting evidence for the magnitude of the potential and the evidence base for land management-based response options can be found as follows: for mitigation tables 6.13 to 6.20, with further evidence in Section 2.6.1; for adaptation tables 6.21 to 6.28; for combating desertification tables 6.29 to 6.36, with further evidence in chapter 3; for combating degradation tables 6.37 to 6.44, with further evidence in chapter 4; for enhancing food security tables 6.29 to 6.36, with further evidence in chapter 5. Other synergies and trade-offs not shown here are discussed in chapter 6.

Seventeen of forty options deliver co-benefits or no adverse side-effects for the full range of NCPs and SDGs; only three options (afforestation, bioenergy and BECCS and some types of risk sharing instruments, such as insurance) have potentially adverse side-effects for five or more NCPs or SDGs (*medium confidence*). The 17 options with co-benefits and no adverse side-effects include most agriculture- and soil-based land management options, many ecosystem-based land management options, improved forest management, reduced post-harvest losses, sustainable sourcing, improved energy use in food systems, and livelihood diversification (*medium confidence*). Some of the synergies between response options and SDGs include positive poverty reduction impacts from activities like improved water management or improved management of supply chains. Examples of synergies between response options and NCPs include positive impacts on habitat maintenance from activities like invasive species management and agricultural diversification. However, many of these synergies are not automatic, and are dependent on well-implemented activities requiring institutional and enabling conditions for success. {6.5}

Most response options can be applied without competing for available land; however, seven options result in competition for land (*medium confidence*). A large number of response options do not require dedicated land, including several land management options, all value chain options, and all risk management options. Four options could greatly increase competition for land if applied at scale: afforestation, reforestation, and land used to provide feedstock for BECCS and biochar, with three further options: reduced grassland conversion to croplands, restoration and reduced conversion of peatlands and restoration and reduced conversion of coastal wetlands having smaller or variable impacts on competition for land. Other options such as reduced deforestation and degradation, restrict land conversion for other options and uses. Expansion of the current area of managed land into natural ecosystems could have negative consequences for other land challenges, lead to the loss of biodiversity, and adversely affect a range of NCPs (*high confidence*). {6.4.6, 6.5}

Some options, such as bioenergy and BECCS, are scale dependent. The climate change mitigation potential for bioenergy and BECCS is large (up to 11 $GtCO_2$ yr^{-1}); however, the effects of bioenergy production on land degradation, food insecurity, water scarcity, GHG emissions, and other environmental goals are scale and context specific (*high confidence*). These effects depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime (*high confidence*). Large areas of monoculture bioenergy crops that displace other land uses can result in land competition, with adverse effects for food production, food consumption, and thus food security, as well as adverse effects for land degradation, biodiversity, and water scarcity (*medium confidence*). However, integration of bioenergy into sustainably managed agricultural landscapes can ameliorate these challenges (*medium confidence*), {6.3, 6.4, 6.5, Cross-Chapter Box 7: Bioenergy and BECCS in Chapter 6}

Response options are interlinked; some options (e.g., land sparing and sustainable land management options) can enhance the co-benefits or increase the potential for other options (*medium confidence*). Some response options can be more effective when applied together (*medium confidence)*; for example, dietary change and waste reduction expand the potential to apply other options by freeing as much as 5.8 Mkm^2 (0.8-2.4 Mkm^2 for dietary change; ~2 Mkm^2 for reduced post-harvest losses, and 1.4 Mkm^2 for reduced food waste) of land (*low confidence*). Integrated water management and increased soil organic carbon can increase food productivity in some circumstances. {6.5}

Other response options (e.g., options that require land) may conflict; as a result, the potentials for response options are not all additive, and a total potential from the land is currently unknown (*high confidence*). Combining some sets of options (e.g., those that compete for land) may mean that maximum potentials cannot be realised, for example reforestation, afforestation, and bioenergy and BECCS all compete for the same finite land resource so the combined potential is much lower than the sum of potentials of each individual option calculated in the absence of alternative uses of the land (*high confidence*). Given the interlinkages among response options and that mitigation potentials for individual options assume that they are applied to all suitable land, the total mitigation potential is much lower than the sum of the mitigation potential of the individual response options (Figure TS. 14) (*high confidence*). {6.5}

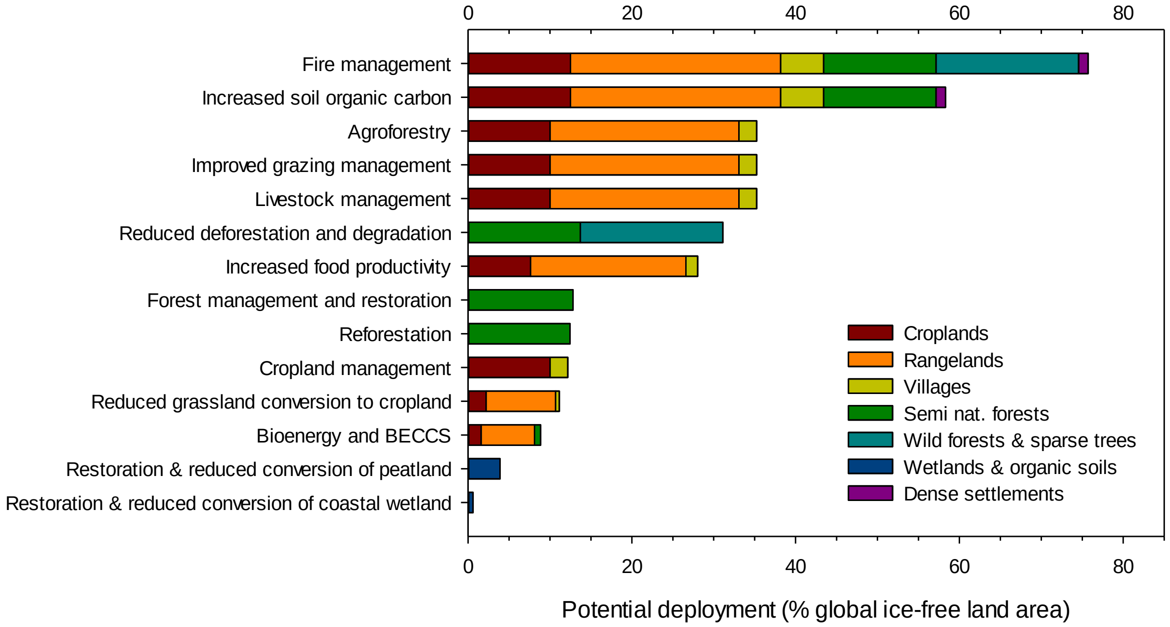

Figure TS. 14 Potential deployment area of land management responses (see Table 6.1) across land use types (or anthromes, see section 6.4), when selecting responses having only co-benefits for local challenges and for climate change mitigation and no large adverse side-effect on global food security. See Figure 6.2 for the criteria used to map challenges (desertification, land degradation, climate change adaptation, chronic undernourishment, biodiversity, groundwater stress and water quality) considered. No response option was identified for barren lands.

The feasibility of response options, including those with multiple co-benefits, is limited due to economic, technological, institutional, socio-cultural, environmental and geophysical barriers (*high confidence*). A number of response options (e.g., most agriculture-based land management options, forest management, reforestation and restoration) have already been implemented widely to date (*high confidence*). There is *robust evidence* that many other response options can deliver co-benefits across the range of land challenges, yet these are not being implemented. This limited application is evidence that multiple barriers to implementation of response options exist (*high confidence*). {6.4, 6.5}

Coordinated action is required across a range of actors, including business, consumers, land managers, indigenous and local communities and policymakers to create enabling conditions for adoption of response options (*high confidence*). The response options assessed face a variety of barriers to implementation (economic, technological, institutional, socio-cultural, environmental and geophysical) that require action across multiple actors to overcome (*high confidence*). There are a variety of response options available at different scales that could form portfolios of measures applied by different stakeholders from farm to international scales. For example, agricultural diversification and use of local seeds by smallholders can be particularly useful poverty reduction and biodiversity conservation measures, but are only successful when higher scales, such as national and international markets and supply-chains, also value these goods in trade regimes, and consumers see the benefits of purchasing these goods. However, the land and food sectors face particular challenges of institutional fragmentation, and often suffer from a lack of engagement between stakeholders at different scales (*medium confidence*). {6.4, 6.5}

Delayed action will result in an increased need for response to land challenges and a decreased potential for land-based response options due to climate change and other pressures (*high confidence*). For example, failure to mitigate climate change will increase requirements for adaptation and may reduce the efficacy of future land-based mitigation options (*high confidence*). The potential for some land management options decreases as climate change increases; for example, climate alters the sink capacity for soil and vegetation carbon sequestration, reducing the potential for increased soil organic carbon (*high confidence*). Other options (e.g., reduced deforestation and degradation) prevent further detrimental effects to the land surface; delaying these options could lead to increased deforestation, conversion, or degradation, serving as increased sources of GHGs and having concomitant negative impacts on NCPs (*medium confidence*). Carbon dioxide removal (CDR) options, like reforestation, afforestation, bioenergy and BECCS, are used to compensate for unavoidable emissions in other sectors; delayed action will result in larger and more rapid deployment later (*high confidence*). Some response options will not be possible if action is delayed too long; for example, peatland restoration might not be possible after certain thresholds of degradation have been exceeded, meaning that peatlands could not be restored in certain locations (*medium confidence*). {6.3, 6.4, 6.5}

Early action, however, has challenges including technological readiness, upscaling, and institutional barriers (*high confidence*). Some of the response options have technological barriers that may limit their wide-scale application in the near-term (*high confidence*). Some response options, e.g., BECCS, have only been implemented at small-scale demonstration facilities; challenges exist with upscaling these options to the levels discussed in this Chapter (*medium confidence*). Economic and institutional barriers, including governance, financial incentives and financial resources, limit the near-term adoption of many response options, and 'policy lags', by which implementation is delayed by the slowness of the policy implementation cycle, are significant across many options (*medium confidence*). Even some actions that initially seemed like 'easy wins' have been challenging to implement, with stalled policies for REDD+ providing clear examples of how response options need sufficient funding, institutional support, local buy-in, and clear metrics for success, among other necessary enabling conditions. {6.3, 6.5}

Some response options reduce the consequences of land challenges, but do not address underlying drivers (*high confidence*). For example, management of urban sprawl can help reduce the environmental impact of urban systems; however, such management does not address the socioeconomic and demographic changes driving the expansion of urban areas. By failing to address the underlying drivers, there is a potential for the challenge to re-emerge in the future (*high confidence*). {6.5}

Many response options have been practiced in many regions for many years; however, there is limited knowledge of the efficacy and broader implications of other response options (*high confidence*). For the response options with a large evidence base and ample experience, further implementation and upscaling would carry little risk of adverse side-effects (*high confidence*). However, for other options, the risks are larger as the knowledge gaps are greater; for example, uncertainty in the economic and social aspects of many land response options hampers the ability to predict their effects (*medium confidence*). Furthermore, Integrated Assessment Models, like those used to develop the pathways in SR1.5, omit many of these response options and do not assess implications for all land challenges (*high confidence*). {6.5}

TS.7. Risk management and Decision Making in Relation 1 to Sustainable Development

Increases in global mean surface temperature are projected to result in continued permafrost degradation and coastal degradation (*high confidence*), increased wildfire, decreased crop yields in low latitudes, decreased food stability, decreased water availability, vegetation loss (*medium confidence)*, decreased access to food and increased soil erosion (*low confidence)*.There is *high agreement and high evidence* that increases in global mean temperature will result in continued increase in global vegetation loss, coastal degradation, as well as decreased crop yields in low latitudes, decreased food stability, decreased access to food and nutrition, and *medium confidence* in continued permafrost degradation and water scarcity in drylands. Impacts are already observed across all components (*high confidence*). Some processes may experience irreversible impacts at lower levels of warming than others. There are high risks from permafrost degradation, and wildfire, coastal degradation, stability of food systems at 1.5°C while high risks from soil erosion, vegetation loss and changes in nutrition only occur at higher temperature thresholds due to increased possibility for adaptation (*medium confidence).* {7.3.2.1, 7.3.2.2, 7.3.2.3; 7.3.2.4; 7.3.2.5; 7.3.2.6; 7.3.2.7; Figure 7.1}

These changes result in compound risks to food systems, human and ecosystem health, livelihoods, the viability of infrastructure, and the value of land *(high confidence*). The experience and dynamics of risk change over time as a result of both human and natural processes (*high confidence*). There is *high confidence* that climate and land changes pose increased risks at certain periods of life (i.e. to the very young and ageing populations) as well as sustained risk to those living in poverty. Responses options may also increase risks. For example, domestic efforts to insulate populations from food price spikes associated with climatic stressors in the mid-2000s inadequately shielded from food insecurity and poverty, and worsened poverty globally (**Figure TS. 15**). {7.3.1, 7.3.2, 7.4, Table 7.1}

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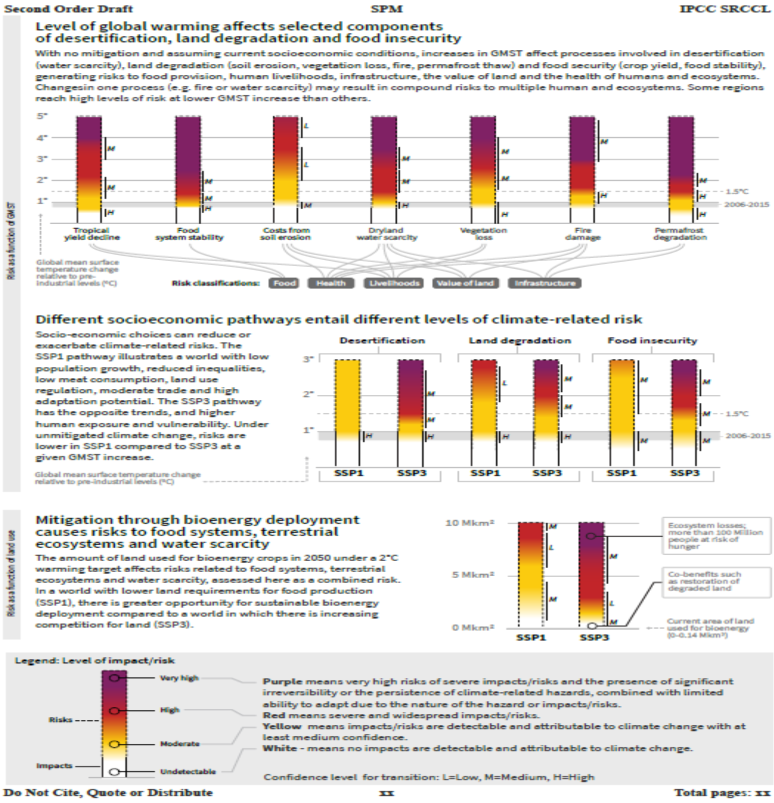

[SPM2]

Figure TS. 15 Risks to land-related human systems and ecosystems from global climate change, socio-economic development and mitigation choices. Panel A: Risks to selected elements of the land system as a function of global mean surface temperature, and their interconnection to broader human and ecological systems (food supply, human and ecosystem health, livelihoods, value of land, and infrastructure). {2.2; Box 2.1; 3.6; 3.8.1.1; 4.5.1.1; 4.5.1.2; 4.5.1.3; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 7.3;7.4}. The land elements shown and their links to broader systems are illustrative of interconnected systems and risks and not intended to be comprehensive. Panel B: Risks associated with desertification, land degradation and food security as a function of climate change and patterns of socio-economic development. Increasing risks associated with desertification include a growing fraction of population exposed and vulnerable to water scarcity and changes in irrigation supply and demand. Risks related to land degradation include increased vegetation loss, population exposed to fire and floods, costs of floods, extent of deforestation, and ecosystem services including the ability of land to sequester carbon. Risks to food security include population at risk of hunger, food price increases, and increases in disability adjusted life years. The risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3 {SPM Fig. 4}) under unmitigated climate change {3.6; 4.3.1.2; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 6.2.4; 7.3}. Panel C: Risks associated with bioenergy crop deployment in 2050 as a land-based mitigation strategy under two socio-economic pathways (SSP1 and SSP3). Risk includes consequences of bioenergy expansion for food security, ecosystem loss and water scarcity. Very high risk indicates that adverse consequences are expected for all three {2.6; 4.6; 5.6.2; 7.3}. The climate scenario considered in Panel C is a mitigation scenario consistent with limiting global warming at 2°C (RCP2.6). For all: As in IPCC SR1.5, AR5 and O'Neill et al. (2017), literature was compiled, and data extracted into a summary table. A formal expert elicitation protocol, based on the modified-Delphi technique and the Sheffield Elicitation Framework, was followed to develop threshold judgments on risk transitions. {7.3, Chapter 7 Supplementary Material}

There is significant regional heterogeneity in risks: tropical regions, including Sub-Saharan Africa, Southeast Asia and Central and South America are particularly vulnerable to decreases in crop yield (*high confidence*). Yield of crops in higher latitudes may initially benefit from warming as well as well from higher CO_2 concentrations. But temperate zones, including the Mediterranean, North Africa, the Gobi Desert, Korea and western United States are susceptible to disruptions from increased drought frequency and intensity, dust storms and fires (*high confidence*). {7.3.2}

Risks related to land degradation, desertification and food security increase with temperature and can reverse development gains in some socio-economic development pathways (*high confidence)*. SSP1 reduces the vulnerability and exposure of human and natural systems and thus limits risks resulting from desertification, land degradation and food insecurity compared to SSP3 (*high confidence*). SSP1 is characterised by low population growth, reduced inequalities, land use regulation, low meat consumption, increased trade and few barriers to adaptation or mitigation. SSP3 has the opposite characteristics. Under SSP1, only a small fraction of the dryland population (around 3% at 3°C for the year 2050) will be exposed and vulnerable to water stress. However under SSP3, already around 20% of dryland populations (for the year 2050) will be exposed and vulnerable to water stress by 1.5°C and 24% by 3°C. Similarly, under SSP1, at 1.5°C, 2 million people are expected to be exposed and vulnerable to crop yield change. Over 20 million are exposed and vulnerable to crop yield change in SSP3, increasing to 854 million people at 3°C (*low confidence*). Livelihoods deteriorate as a result of these impacts, livelihood migration is accelerated, and strife and conflict is worsened (*medium confidence*). {Cross-Chapter Box 9: Illustrative Climate and Land Pathways in Chapter 6, 7.3.2, 7.4.2, Table 7.1, Figure 7.2}

Land-based adaptation and mitigation responses pose risks associated with the effectiveness and potential adverse side-effects of measures chosen (*high confidence*). Adverse side-effects on food security, ecosystem services and water security increase with the scale of bioenergy and bioenergy with carbon capture and storage (BECCS) deployment. In a SSP1 future, bioenergy and BECCS deployment up to 6 Mkm^2 is compatible with sustainability constraints, whereas risks are already high in a SSP3 future for this scale of deployment. {7.3.3}

There is *high confidence* that policies addressing vicious cycles of poverty, land degradation and greenhouse gas emissions in a holistic manner can achieve climate resilient sustainable development. Choice and implementation of policy instruments determine future climate and land pathways (*medium confidence)*. Sustainable development pathways (described in SSP1) supported by effective regulation of land use to reduce environmental trade-offs, reduced reliance on traditional biomass, low growth in consumption and limited meat diets, moderate international trade with connected regional markets, and effective GHG mitigation instruments) can result in lower food prices, fewer people affected by floods and other climatic disruptions, and increases in forested land (*high agreement, limited evidence*) (SSP1). A policy pathway with limited regulation of land use, low technology development, resource intensive consumption, constrained trade, and ineffective GHG mitigation instruments can result in food price increases, and significant loss of forest (*high agreement, limited evidence*) (SSP3). {3.8.5, 7.3.2, 7.4.4, 7.6.5, 7.6.6, Table 7.1, Cross-Chapter Box 12: Traditional Biomass Use in Chapter 7}

Delaying deep mitigation in other sectors and shifting the burden to the land sector, increases the risk associated with adverse effects on food security and ecosystem services (high confidence). The consequences are an increased pressure on land with higher risk of mitigation failure and of temperature overshoot and a transfer of the burden of mitigation and unabated climate change to future generations.

Prioritising early decarbonisation with minimal reliance on carbon dioxide removal (CDR) decreases the risk of mitigation failure (high confidence). {2.6, 6.3, 6.5, 7.3.1, 7.3.2, 7.3.3, 7.6.6, 7.6.7, Cross-Chapter Box 9: Illustrative Climate and Land Pathways in Chapter 6, 7.6.6}

Trade-offs can occur between using land for climate mitigation or sustainable development goal (SDG) 7 (affordable clean energy) with biodiversity, food, ground-water and riverine ecosystem services (medium confidence). There is medium confidence that trade-offs currently do not figure into climate policies and decision making. Small hydro power installations (especially in clusters) can impact downstream river ecological connectivity for fish (high agreement, medium evidence). Large scale solar farms and wind turbine installations can impact endangered species and disrupt habitat connectivity (medium agreement, medium evidence). Conversion of rivers for transportation can disrupt fisheries and endangered species (through dredging and traffic) (medium agreement, low evidence). {7.6.6}

The full mitigation potential assessed in this report will only be realised if agricultural emissions are included in mainstream climate policy (high agreement, high evidence). Carbon markets are theoretically more cost-effective than taxation but challenging to implement in the land-sector (high confidence) Carbon pricing (through carbon markets or carbon taxes) has the potential to be an effective mechanism to reduce GHG emissions, although it remains relatively untested in agriculture and food systems. Equity considerations can be balanced by a mix of both market and non-market mechanisms (medium evidence, medium agreement). Emissions leakage could be reduced by multi-lateral action (high agreement, medium evidence). {7.5.6, 7.6.5, 7.6.6, Cross-Chapter Box 9: Illustrative Land and Climate Pathways in Chapter 6}

A suite of coherent climate and land policies advances the goal of the Paris Agreement and the land-related SDG targets on poverty, hunger, health, sustainable cities and communities, responsible consumption and production, and life on land. There is *high confidence* that acting early will avert or minimise risks, reduce losses and generate returns on investment. The economic costs of action on sustainable land management, mitigation, and adaptation are less than the consequences of inaction for humans and ecosystems (*medium confidence*). Policy portfolios that make ecological restoration more attractive, people more resilient - expanding financial inclusion, flexible carbon credits, disaster risk and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems – could save USD 100 billion a year, if implemented globally. {7.4.1, 7.5.7, 7.5.8, 7.6.6, Cross-Chapter Box 10: Economic Dimensions in Chapter 7}

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

Figure TS. 16). {3.8.5, Cross-Chapter Box 5: Policy Responses to Drought in Chapter 3, 7.5.3, 7.5.6, 7.6.6, 7.5.8, 7.6.6, 7.7.3}

Table TS. 1 Selection of Policies/Programmes/Instruments that support response options.

Category	Integrated Response Option	Policy instrument supporting response option
Land management in agriculture	Increased food productivity	Investment in agricultural research for crop and livestock improvement, agricultural technology transfer, inland capture fisheries and aquaculture {7.5.7} agricultural policy reform and trade liberalisation
	Improved cropland, grazing, and livestock management	Environmental farm programs/agri-environment schemes, water efficiency requirements and water transfer {3.8.5}, extension services
	Agroforestry	Payment for ecosystem services {7.5.6}
	Agricultural diversification	Elimination of agriculture subsidies {5.7.1}, environmental farm programs, agri-environmental payments {7.5.6}, rural development programmes
	Reduced grassland conversion to cropland	Elimination of agriculture subsidies, remove insurance incentives, ecological restoration {7.5.6}
	Integrated water management	Integrated governance {7.7.2}, multi-level instruments [7.5.1}
Land management in forests	Forest management, Reduced deforestation and degradation, Reforestation and forest restoration, Afforestation	REDD+, forest conservation regulations, payments for ecosystem services, recognition of forest rights and land tenure {7.5.6}, adaptive management of forests {7.6.4}, land use moratoriums, reforestation programs and investment {4.10.1}
Land management of soils	Increased soil organic carbon content, Reduced soil erosion, Reduced soil salinisation, Reduced soil compaction, Biochar addition to soil	Land degradation neutrality {7.5.5}, drought plans, flood plans, flood zone mapping{7.5.3}, technology transfer (7.5.4}, land use zoning {7.5.6}, ecological service mapping and stakeholder based quantification {7.6.3}, environmental farm programs/agri-environment schemes, water efficiency requirements and water transfer {3.8.5}
Land management in all other ecosystems	Fire management	Fire suppression, prescribed fire management, mechanical treatments {7.5.3}
	Reduced landslides and natural hazards	Land use zoning {7.5.6}
	Reduced pollution - acidification	Environmental regulations, Climate mitigation (carbon pricing) {7.5.4}
	Management of invasive species / encroachment	Invasive species regulations, trade regulations {5.7.2, 7.5.6}
	Restoration and reduced conversion of coastal wetlands	Flood zone mapping {7.5.3}, land use zoning {7.5.6}
	Restoration and reduced conversion of peatlands	Payment for ecosystem services {7.5.6; 7.6.3}, standards and certification programs {7.5.6}, land use moratoriums
	Biodiversity conservation	Conservation regulations, protected areas policies
CDR Land management	Enhanced weathering of minerals	No data
	Bioenergy and BECCS	Standards and certification for sustainability of biomass and land use {7.5.6}
Demand management	Dietary change	Awareness campaigns/education, changing food choices through nudges, synergies with health insurance and policy {5.7.2}
	Reduced post-harvest losses Reduced food waste (consumer or retailer), Material substitution	Agricultural business risk programs {7.5.8}; regulations to reduce and taxes on food waste, Improved shelf life, circularising the economy to produce substitute goods, carbon pricing, sugar/fat taxes {5.7.2}
Supply management	Sustainable sourcing	Food labelling, innovation to switch to food with lower environmental footprint, public procurement policies {5.7.2}, standards and certification programs {7.5.6}
	Management of supply chains	Liberalised international trade {5.7.2}, food purchasing and storage policies of governments, standards and certification programs {7.5.6}, regulations on speculation in food systems
	Enhanced urban food systems	Buy local policies; land use zoning to encourage urban agriculture, nature-based solutions and green infrastructure in cities; incentives for technologies like vertical farming
	Improved food processing and retailing, Improved energy use in food systems	Agriculture emission trading {7.5.4}; investment in research and development for new technologies; certification
	Management of urban sprawl	Land use zoning {7.5.6}

Risk management	Livelihood diversification	Climate-smart agriculture policies, adaptation policies, extension services {7.6.6}
	Disaster risk management	Disaster risk reduction {7.6.4; 7.5.3}, adaptation planning
	Risk sharing instruments	Insurance, iterative risk management, Cat bonds, risk layering, contingency funds {7.5.3}, agriculture business risk portfolios {7.5.8}


IPCC SRCCL
Second Order Draft
SPM
Illustrative pathways linking policy, land use and climate change
Socioeconomic development influences the evolution of the land system including the relative amount of land allocated to agriculture, energy crops, and forest. This has implications for climate change mitigation, adaptation and other sectoral characteristics. The lines shows the range across models for three alternative shared socioeconomic pathways: SSP1 (green), SSP2 (blue), and SSP3 (magenta), under two different warming targets in 1.5°C and 2.5 to 3°C scenarios. Note that 1.5 °C is not possible from SSP3 and thus is excluded.
AGRICULTURE and Socio-Economic Development
SSP1 has the lowest agricultural land expansion. This socio-economic pathway is characterised by sustainable land management, the achievement of Land Degradation Neutrality targets, sustainable intensification, enhancement of ecosystem services, changing dietary patterns, and the reduction of food waste. Sustainable land management and demand side changes are not included in SSP3. SSP2 is similar to SSP1, but changes start later and are less effective.
BIOENERGY and Socio-Economic Development
All pathways use bioenergy, with more use in the SSP2 and SSP3 than in the SSP1. All three pathways include carbon prices that incentivise bioenergy use. The presence of other response options, including sustainable land management, however, results in less bioenergy in the SSP1 than the SSP3. In the SSP2, more bioenergy is needed sooner than in the SSP1 to compensate for other emissions.
FOREST and Socio-Economic Development
SSP1 has the greatest forest expansion. This socio-economic pathway is characterised by land use regulation, forest protection, and biodiversity preservation, including incentives for reforestation and afforestation. Forest expansion is primarily on abandoned agricultural land, resulting in less competition for land than in SSP2. SSP2 is similar to SSP1, but changes start later and have less impact. Land use regulation and biodiversity conservation are absent in SSP3.
Change in Agriculture Land 1.5 °C
Mkm²
Agricultural land area declines in both the SSP1 and SSP2 scenarios
Change in Energy Cropland 1.5 °C
Mkm²
More land for bioenergy and earlier deployment for SSP2 compared to SSP1
Change in Forest Cover 1.5 °C
Mkm²
SSP1 includes more afforestation than SSP2
1.5°C
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Figure TS. 16 Illustrative pathways linking policy, land use and climate change.

Illustrative pathways linking policy, land use and climate change. Future pathways provide a framework for understanding the implications of policy and socioeconomics on land and climate. These scenarios use the Shared Socioeconomic Pathways (SSPs) {6.2, Cross-Chapter Box 2: 'Implications of large-scale conversion from non-forest to forest land' in Chapter 1, Cross-chapter box 9: 'Illustrative Climate and Land Pathways' in Chapter 6, SPM Box A7} to span a range of different socioeconomic assumptions, policies, and warming levels. They were selected to show different future land use evolutions and their implications for land cover, emissions, and prices. The change in agricultural land (including non-energy crops and pasture), bioenergy cropland, and forest land from 2010 are shown. For each pathway, the shaded areas show the range across all models that represent all SSPs for a particular warming level. SSP1 is shown in green, SSP2 in blue, and SSP3 in magenta for 1.5˚C (first row) and 2.5 to 3˚C (second row) pathways; the line indicates the median across models. Further characteristics for each of these pathways are listed in the figure table. All indicators in the table are outcomes of integrated assessment models (IAMs) and include the full range of model pathways. Limiting global warming to 1.5˚C is not possible under SSP3 and thus this pathway is excluded; in addition, two models cannot limit warming to 1.5˚C in SSP2 {2.7, 6.2, 7.6, Cross-chapter box 9: 'Illustrative Climate and Land Pathways' in Chapter 6}. Additional risks related to bioenergy expansion are shown in SPM Fig. 2 Panel C. Pathways are labelled by their long-term temperature levels (either 1.5˚C or 2.5 to 3˚C). Temperature rise in 2100 is 1.3ºC in the 1.5ºC pathways and 2.6ºC in the 2.5 to 3ºC pathways. Pathways include effects of mitigation, but exclude climate change impacts on society, and do not account for the biophysical feedbacks of land on regional climate. SPM Fig. 2 panel b shows these effects for pathways SSP1 and SSP3. {3.8.5, 4.10.1, 5.7.1, 5.7.2, 6.5.4, 7.5.2, 7.5.4, 7.5.5, 7.5.6, 7.5.7, 7.5.8, 7.6.3, 7.6.6; Cross-Chapter Box 9: 'Illustrative Climate and Land Pathways' in Chapter 6}

Technology transfer in land use sectors offers new opportunities for adaptation, mitigation, international cooperation, R&D collaboration, and local engagement (*medium confidence*). International cooperation to modernise the traditional biomass sector will free up both land and labour for more productive uses. Technology transfer can assist the measurement and accounting of emission reductions by developing countries. {7.5.4, 7.5.6}

Measuring progress towards goals is important in decision-making and adaptive governance to create common understanding and advance policy effectiveness (*high agreement, medium evidence*). Measurable indicators, selected with the participation of people and supporting data collection, are useful for climate policy development and decision-making. Indicators include the SDGs, nationally determined contributions (NDCs), land degradation neutrality (LDN) core indicators, carbon stock measurement, measurement and monitoring for REDD+, metrics for measuring biodiversity and ecosystem services, and governance capacity. {7.6.5, 7.6.7, 7.7.4, 7.7.6}

The complex spatial, cultural and temporal dynamics of risk and uncertainty in relation to land and climate interactions and food security, require a flexible, adaptive, iterative approach to assessing risks, revising decisions and policy instruments (*high confidence*). Adaptive, iterative decision-making moves beyond standard economic appraisal techniques to new methods such as dynamic adaptation pathways with risks identified by trigger points through indicators. Scenarios can provide valuable information at all planning stages in relation to land, climate and food; adaptive management addresses uncertainty in scenario planning with pathway choices made and reassessed to respond to new information and data as it becomes available. {3.8.5, 7.5.4, 7.6.2, 7.6.3, 7.6.4, 7.6.7, 7.7.1, 7.7.3}

Indigenous and local knowledge (ILK) can play a key role in understanding climate processes and impacts, adaptation to climate change, sustainable land management across different ecosystems, and enhancement of food security (*high confidence*). ILK is context-specific, collective, informally transmitted, and multi-functional, and can encompass factual information about the environment and guidance on management of resources and related rights and social behaviour. ILK can be used in decision-making at various scales and levels, and exchange of experiences with adaptation and mitigation that include ILK is both a requirement and an entry strategy for participatory climate communication and action. Opportunities exist for integration of ILK with scientific knowledge. {7.5.1, 7.5.5, 7.5.6, 7.7.4, Cross-Chapter Box 13: ILK in Chapter 7}

Participation of people in land and climate decision making and policy formation allows for transparent effective solutions and the implementation of response options that advance synergies, reduce trade-offs in sustainable land management (*high confidence*), and overcomes barriers to adaptation and mitigation (high confidence). Improvements to sustainable land management are achieved by: (1) engaging people in citizen science by mediating and facilitating landscape conservation planning, policy choice, and early warning systems (*medium confidence*); (2) involving people in identifying problems (including species decline, habitat loss, land use change in agriculture, food production and forestry), selection of indicators, collection of climate data, land modelling, agricultural innovation opportunities. When social learning is combined with collective action, transformative change can occur addressing tenure issues and changing land use practices (*medium confidence*). Meaningful participation overcomes barriers by opening up policy and science surrounding climate and land decisions to inclusive discussion that promotes alternatives. {3.8.5, 7.5.1, 7.5.9; 7.6.1, 7.6.4, 7.6.5, 7.6.7, 7.7.4, 7.7.6}

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

The significant social and political changes required for sustainable land use, reductions in demand and land-based mitigation efforts associated with climate stabilisation require a wide range of governance mechanisms. The expansion and diversification of land use and biomass systems and markets requires hybrid governance: public-private partnerships, transnational, polycentric, and state governance to insure opportunities are maximised, trade-offs are managed equitably, and negative impacts are minimised (*medium confidence*). {7.5.6, 7.7.2, 7.7.3, Cross-Chapter Box 7: Bioenergy and BECCS in Chapter 6}

Land tenure systems have implications for both adaptation and mitigation, which need to be understood within specific socio-economic and legal contexts, and may themselves be impacted by climate change and climate action (*limited evidence, high agreement*). Land policy (in a diversity of forms beyond focus on freehold title) can provide routes to land security and facilitate or constrain climate action, across cropping, rangeland, forest, fresh-water ecosystems and other systems. Large-scale land acquisitions are an important context for the relations between tenure security and climate change, but their scale, nature and implications are imperfectly understood. There is medium confidence that land titling and recognition programs, particularly those that authorise and respect indigenous and communal tenure, can lead to improved management of forests, including for carbon storage. Strong public coordination (government and public administration) can integrate land policy with national policies on adaptation and reduce sensitivities to climate change. {7.7.2; 7.7.3; 7.7.4, 7.7.5}

Significant gaps in knowledge exist when it comes to understanding the effectiveness of policy instruments and institutions related to land use management, forestry, agriculture and bioenergy. Interdisciplinary research is needed on the impacts of policies and measures in land sectors. Knowledge gaps are due in part to the highly contextual and local nature of land and climate measures and the long time periods needed to evaluate land use change in its socio-economic frame, as compared to technological investments in energy or industry that are somewhat more comparable. Significant investment is needed in monitoring, evaluation and assessment of policy impacts across different sectors and levels. {7.8}