Technical Summary

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TS.0 Introduction

This Technical Summary to the IPCC Special Report on Climate Change and Land (SRCCL)[1] comprises a compilation of the chapter executive summaries illustrated with figures from the report. It follows the structure of the SRCCL (Figure TS.1) 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.2). 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. TS.7 (Chapter 7) further assesses decision making and policy responses to risks in the climate-land-human system.

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 the multiple resources, services and livelihood systems provided by land ecosystems and biodiversity. The annual value of the world's total terrestrial ecosystem services has been estimated at 75 trillion USD in 2011, approximately equivalent to the annual global Gross Domestic Product (based on USD2007 values) (*medium confidence*). Land and its biodiversity also represent essential, intangible benefits to humans, such as cognitive and spiritual enrichment, sense of belonging and aesthetic and recreational values. Valuing ecosystem services with monetary methods often overlooks these intangible services that shape societies, cultures and quality of life and the intrinsic value of biodiversity. The Earth's land area is finite. Using land resources sustainably is fundamental for human well-being (*high confidence*). {1.1.1}

The current geographic spread of the use of land, the large appropriation of multiple ecosystem services and the loss of biodiversity are unprecedented in human history (*high confidence*). By 2015, about three-quarters of the global ice-free land surface was affected by human use. Humans appropriate one-quarter to one-third of global terrestrial potential net primary production (*high confidence*). Croplands cover 12–14% of the global ice-free surface. Since 1961, the supply of global per capita food calories increased by about one-third, with the consumption of vegetable oils and meat more than doubling. At the same time, the use of inorganic nitrogen fertiliser increased by nearly ninefold, and the use of irrigation water roughly doubled (*high confidence*). Human use, at varying intensities, affects about 60–85% of forests and 70–90% of other natural ecosystems (e.g., savannahs, natural grasslands) (*high confidence*). Land use caused global biodiversity to decrease by around 11–14% (*medium confidence*). (Figure TS.2). {1.1.2}

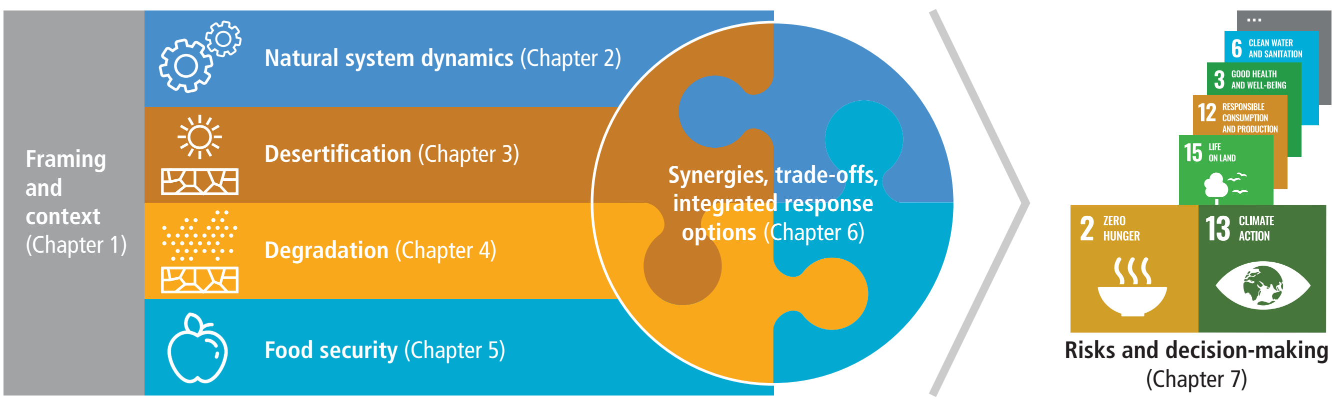


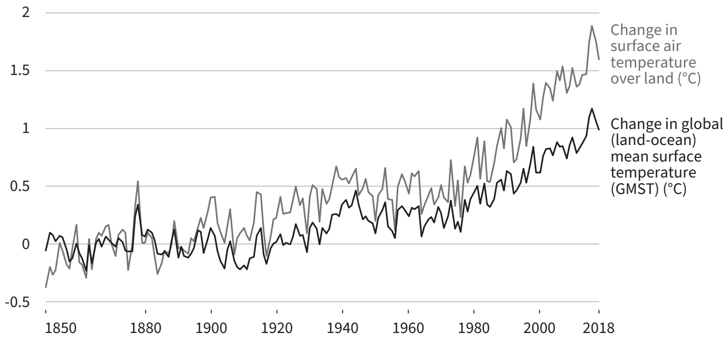
Figure TS.1 | Overview of the IPCC Special Report on Climate Change and Land (SRCCL).

[1] 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*

Land use and observed climate change

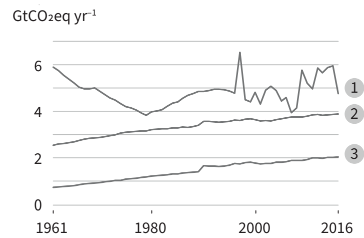
A. Observed temperature change relative to 1850–1900
Since the pre-industrial period (1850–1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST).

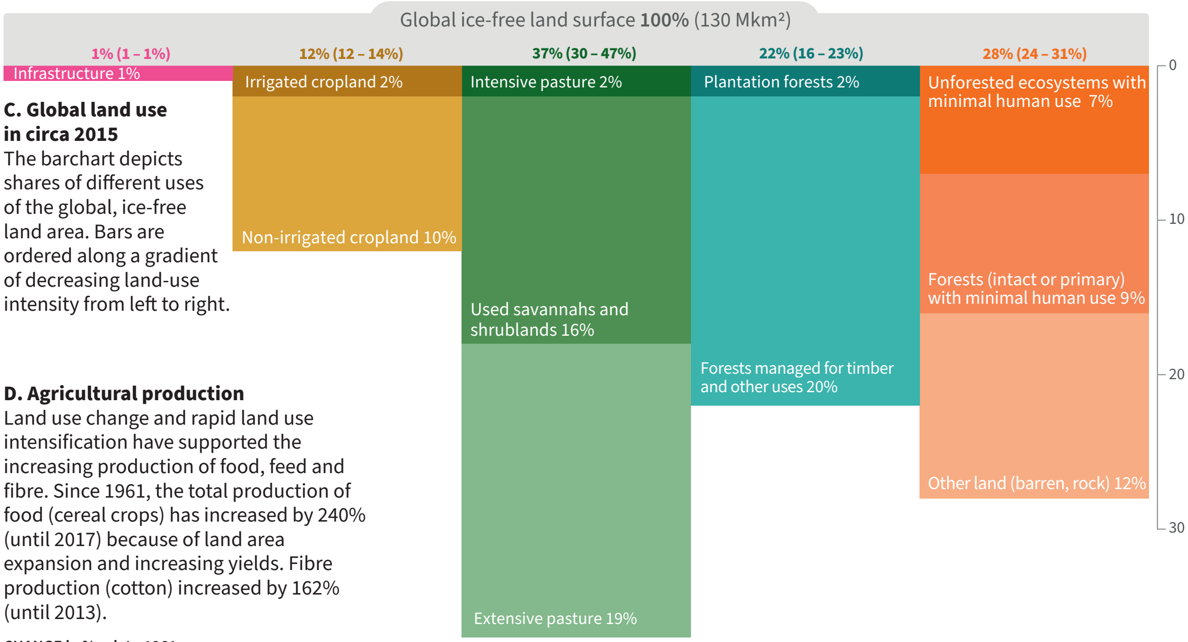
CHANGE in TEMPERATURE rel. to 1850–1900 (°C)



B. GHG emissions
An estimated 23% of total anthropogenic greenhouse gas emissions (2007–2016) derive from Agriculture, Forestry and Other Land Use (AFOLU).

CHANGE in EMISSIONS since 1961
1 Net CO_2 emissions from FOLU ($GtCO_2$ yr^{-1})
2 CH_4 emissions from Agriculture ($GtCO_2eq$ yr^{-1})
3 N_2O emissions from Agriculture ($GtCO_2eq$ yr^{-1})

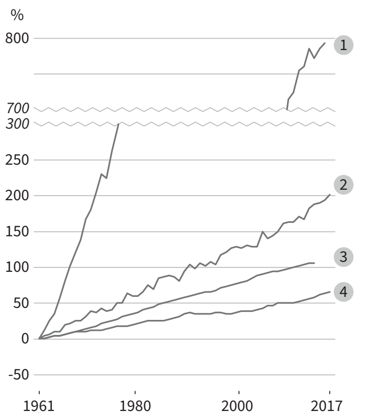




C. Global land use in circa 2015
The barchart depicts shares of different uses of the global, ice-free land area. Bars are ordered along a gradient of decreasing land-use intensity from left to right.

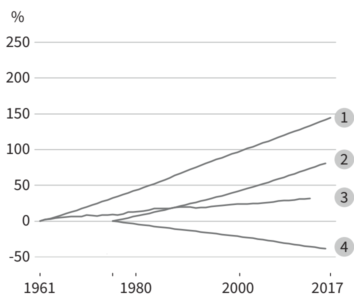
D. Agricultural production
Land use change and rapid land use intensification have supported the increasing production of food, feed and fibre. Since 1961, the total production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields. Fibre production (cotton) increased by 162% (until 2013).

CHANGE in % rel. to 1961
1 Inorganic N fertiliser use
2 Cereal yields
3 Irrigation water volume
4 Total number of ruminant livestock



E. Food demand
Increases in production are linked to consumption changes.

CHANGE in % rel. to 1961 and 1975
1 Population
2 Prevalence of overweight + obese
3 Total calories per capita
4 Prevalence of underweight



F. Desertification and land degradation
Land-use change, land-use intensification and climate change have contributed to desertification and land degradation.

CHANGE in % rel. to 1961 and 1970
1 Population in areas experiencing desertification
2 Dryland areas in drought annually
3 Inland wetland extent

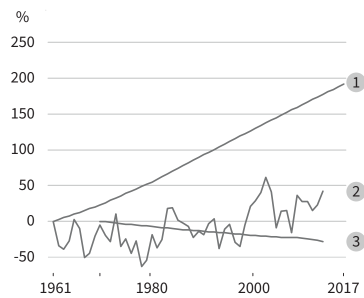


Figure TS.2 | Land use and observed climate change: A representation of the principal land challenges and land–climate system processes covered in this assessment report.

Figure TS.2 (continued): Panels A-F show the status and trends in selected land use and climate variables that represent many of the core topics covered in this report. The annual time series in B and D–F are based on the most comprehensive, available data from national statistics, in most cases from FAOSTAT which starts in 1961. Y-axes in panels D–F are expressed relative to the starting year of the time series (rebased to zero). Data sources and notes: **A:** The warming curves are averages of four datasets {2.1; Figure 2.2; Table 2.1} **B:** N_2O and CH_4 from agriculture are from FAOSTAT; Net CO_2 emissions from FOLU using the mean of two bookkeeping models (including emissions from peatland fires since 1997). All values expressed in units of CO_2-eq are based on AR5 100-year Global Warming Potential values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28). {see Table SPM.1, 1.1, 2.3} **C:** Depicts shares of different uses of the global, ice-free land area for approximately the year 2015, ordered along a gradient of decreasing land-use intensity from left to right. Each bar represents a broad land cover category; the numbers on top are the total % of the ice-free area covered, with uncertainty ranges in brackets. Intensive pasture is defined as having a livestock density greater than 100 animals/km². The area of 'forest managed for timber and other uses' was calculated as total forest area minus 'primary/intact' forest area. {1.2, Table 1.1, Figure 1.3} **D:** Note that fertiliser use is shown on a split axis. The large percentage change in fertiliser use reflects the low level of use in 1961 and relates to both increasing fertiliser input per area as well as the expansion of fertilised cropland and grassland to increase food production. {1.1, Figure 1.3} **E:** Overweight population is defined as having a body mass index (BMI) >25 kg m^{-2}; underweight is defined as BMI <18.5 kg m^{-2}. {5.1, 5.2} **F:** Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980–2015) to identify areas where the Aridity Index is below 0.65. Population data are from the HYDE3.2 database. Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index. The inland wetland extent (including peatlands) is based on aggregated data from more than 2000 time series that report changes in local wetland area over time. {3.1, 4.2, 4.6}

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

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

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

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

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

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

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

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

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

TS.2 Land–climate interactions

Implications of climate change, variability and extremes for land systems

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 the preindustrial period (1850–1900) to the present day (1999–2018). According to the single longest and most extensive dataset, from 1850–1900 to 2006–2015 mean land surface air temperature has increased by 1.53°C (*very likely range* from 1.38°C to 1.68°C) while global mean surface temperature has increased by 0.87°C (*likely range* from 0.75°C to 0.99°C). For the 1881–2018 period, when four independently produced datasets exist, the LSAT increase was 1.41°C (1.31–1.51°C), 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 1.54–1.81). {2.2.1}

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 latitude and upward in regions of higher elevation (*high confidence*). Ecosystems in these regions will become increasingly exposed to temperature and rainfall extremes beyond the 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*). {2.2.1, 2.2.2, 2.5.3}

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 heatwaves are projected in a warmer climate. There is *low confidence* in the projections of global greening and browning trends. {2.2.4, Cross-Chapter Box 4 in Chapter 2}

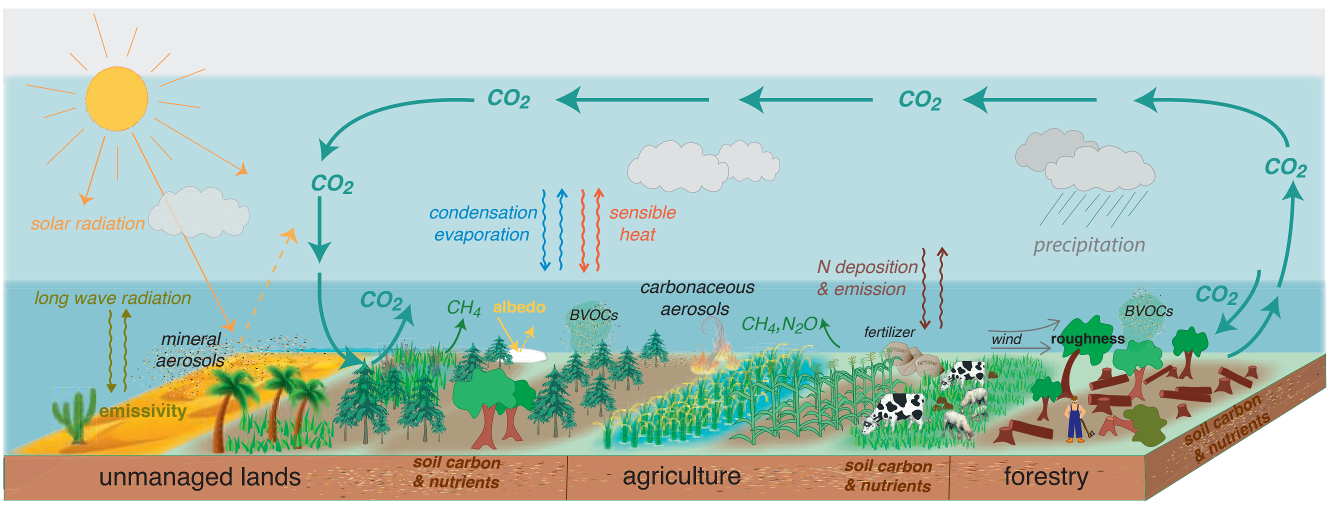


Figure TS.3 | The structure and functioning of managed and unmanaged ecosystems that affect local, regional and global climate. Land surface characteristics such as albedo and emissivity determine the amount of solar and long-wave radiation absorbed by land and reflected or emitted to the atmosphere. 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 the amounts of precipitation and radiation reaching land surfaces through their role in clouds physics.

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, for example, heatwaves, have been made more frequent or intense due to anthropogenic GHG 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*). Heatwaves 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 GHG fluxes (*high confidence*). {2.2.5}

Climate change is playing an increasing role in determining wildfire regimes alongside 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 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 23% of anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) combined as CO_2 equivalents in 2007–2016 (*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*). (Figure TS.3) {2.3}

The total net land-atmosphere flux of CO_2 on both managed and unmanaged lands *very likely* provided a global net removal from 2007 to 2016 according to models (-6.0 ± 3.7 $GtCO_2\,yr^{-1}$, *likely range*). This net removal is comprised of two major components: (i) modelled net anthropogenic emissions from AFOLU are 5.2 ± 2.6 $GtCO_2\,yr^{-1}$ (*likely range*) 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 11.2 ± 2.6 $GtCO_2\,yr^{-1}$ (*likely range*) 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*). {2.3.1}

Global models and national GHG inventories use different methods to estimate anthropogenic CO_2 emissions and removals for the land sector. Consideration of differences in methods can enhance understanding of land sector net emission such as under the Paris Agreement's global stocktake (*medium confidence*). Both models and inventories produce estimates that are in close agreement for land-use change involving forest (e.g., deforestation, afforestation), and differ for managed forest. Global models consider as managed forest those lands that were subject to harvest whereas, consistent with IPCC guidelines, national GHG inventories define managed forest more broadly. On this larger area, inventories can also consider the natural response of land to human-induced environmental changes as anthropogenic, while the global model approach treats this response as part of the non-anthropogenic sink. For illustration, from 2005 to 2014, the sum of the national GHG inventories net emission estimates is 0.1 ± 1.0 $GtCO_2\,yr^{-1}$, while the mean of two global bookkeeping models is 5.1 ± 2.6 $GtCO_2yr^{-1}$ (*likely range*). {Table SPM.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: (i) gross emissions (20 $GtCO_2\,yr^{-1}$) from deforestation, cultivation of soils and oxidation of wood products, and (ii) gross removals (–14 $GtCO_2\,yr^{-1}$), largely from forest growth following wood harvest and agricultural abandonment (*medium confidence*). (Figure TS.4) {2.3.1}

Land is a net source of CH_4, accounting for 44% of anthropogenic CH_4 emissions for the 2006–2017 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 13C 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*). {2.3.2}

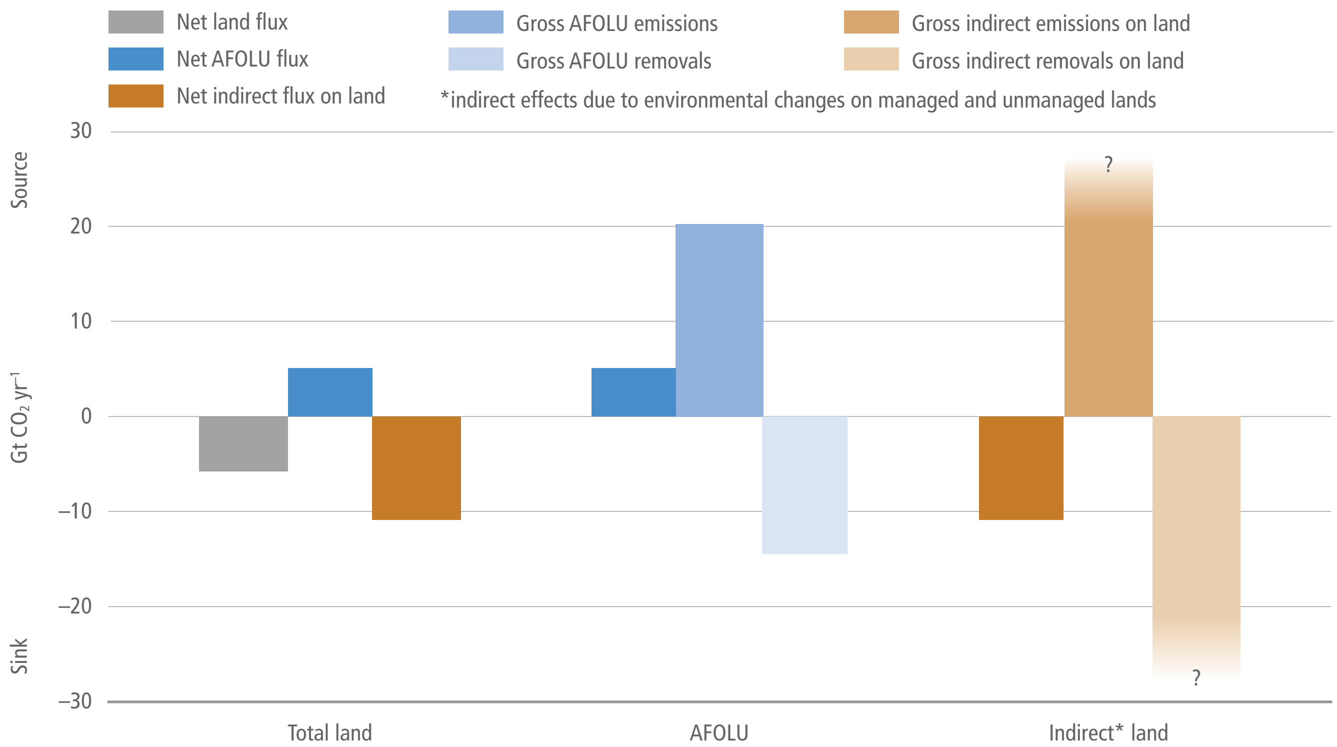


Figure TS.4 | Net and gross fluxes of CO_2 from land (annual averages for 2008–2017). Left: The total net flux of CO_2 between land and atmosphere (grey) is shown with its two component fluxes, (i) net AFOLU emissions (blue), and (ii) the net land sink (brown), due to indirect environmental effects and 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.

AFOLU is the main anthropogenic source of N_2O primarily due to nitrogen application to soils (*high confidence*). In croplands, the main driver of N_2O emissions is a lack of synchronisation between crop nitrogen demand and soil nitrogen supply, with approximately 50% of the nitrogen applied to agricultural land not taken up by the crop. Cropland soils emit over 3 MtN_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 nitrogen application rates dominate, such as sub-Saharan Africa and parts of Eastern Europe, increases in nitrogen 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*). {2.3.3}

While managed pastures make up only one-quarter of grazing lands, they contributed more than three-quarters of N_2O emissions from grazing lands between 1961 and 2014 with rapid recent increases of nitrogen 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*). {2.3.3}

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*). {2.3.1, 2.7.2, 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 biophysical effects influence global climate. {2.1, 2.3, 2.5.1, 2.5.2}

Changes in land conditions modulate the likelihood, intensity and duration of many extreme events including heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*). Dry soil conditions favour or strengthen summer heatwave 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*). {2.5.1, 2.5.2, 2.5.3}

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. {2.3, 2.5.1, 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 is 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). {2.5.2}

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 the 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*). {2.5.2, 2.5.3}

According to model-based studies, changes in local land cover or available water from irrigation will 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 altering regional winds and consequently moisture and temperature advection and convection and subsequently, precipitation. {2.5.2, 2.5.4, Cross-Chapter Box 4 in Chapter 2}

Future increases in both climate change and urbanisation will enhance warming in cities and their surroundings (urban heat island), especially during heatwaves (*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 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, inter-annual 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*). {2.4, 2.5}

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 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*). {2.6.3}

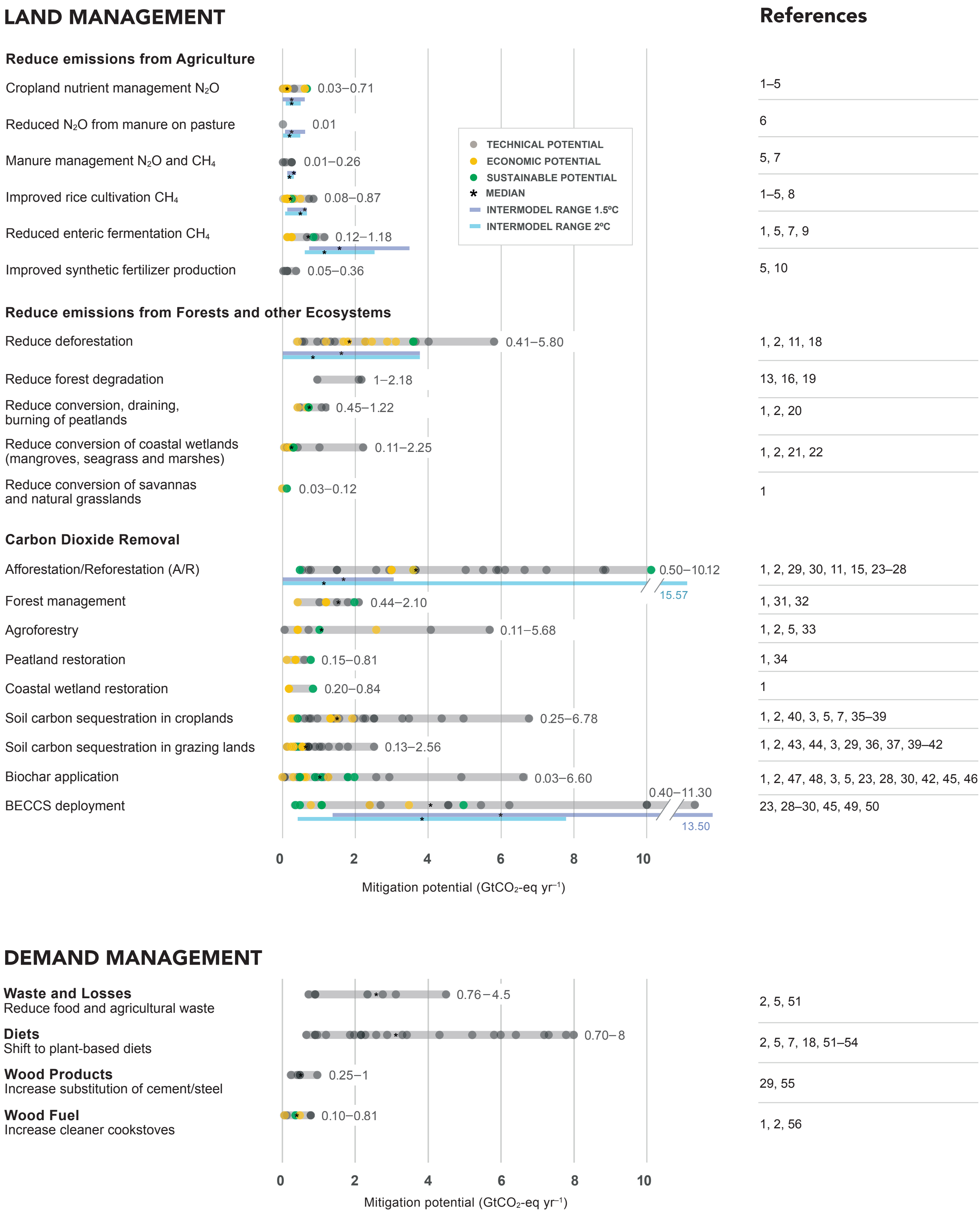


Figure TS.5 | Mitigation potential of response options in 2020–2050, measured in GtCO2-eq yr[−1], adapted from Roe et al. (2017).

Figure TS.5 (continued): 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 more than four data points. We only include references that explicitly provide mitigation potential estimates in CO_2-eq yr^{-1} (or a similar derivative) by 2050. Not all options for 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 IAMs 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'.

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 y^{r-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. {2.6.1}

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*). {2.5.2, 2.5.4, 2.7, Cross-Chapter Box 4 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 $GtCO_2$yr^{-1} for scenarios RCP4.5, RCP2.6 and RCP1.9 respectively) and BECCS (–6.5, –11 and –14.9 $GtCO_2$ yr^{-1} respectively). 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 on global and regional warming. {2.5, 2.6.2}

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 to 6.6 Mkm^2 in 2100 (*high confidence*). Large-scale land-based CDR is associated with multiple feasibility and sustainability constraints. 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.5) {2.6.2, Chapters 6, 7}

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*). {2.6.2}

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 the 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, the circum Sahara region including North Africa and the Middle East including the Arabian Peninsula (*low confidence*). Other dryland regions have also experienced desertification. 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 well-being in drylands and beyond (*high confidence*). Dust storms were associated with global cardiopulmonary mortality of about 402,000 people in 2005. 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.6) {3.1.1, 3.1.4, 3.2.1, 3.3.1, 3.4.1, 3.4.2, 3.4.2, 3.7.3, 3.7.4}

Attribution of desertification to climate variability and change, and to 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*). {3.1.4, 3.2.2, 3.4.2}

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. {3.1.1, 3.2.2, 3.5.1, 3.5.2, 3.7.1, 3.7.3}

Risks from desertification are projected to increase due to climate change (*high confidence*). Under shared socio-economic 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) is projected to reach 951 (178) million, 1152 (220) million and 1285 (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 1267 (522) million. Around half of the vulnerable population is in South Asia, followed by Central Asia, West Africa and East Asia. {2.2, 3.1.1, 3.2.2, 3.5.1, 3.5.2, 7.2.2}

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*). {3.1.4, 3.4.1, 3.5.2, 3.7.3}

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*). {3.4.2, 3.6.2}

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 (rather than temperature) controls CO_2 exchange has increased by 6% between 1948 and 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

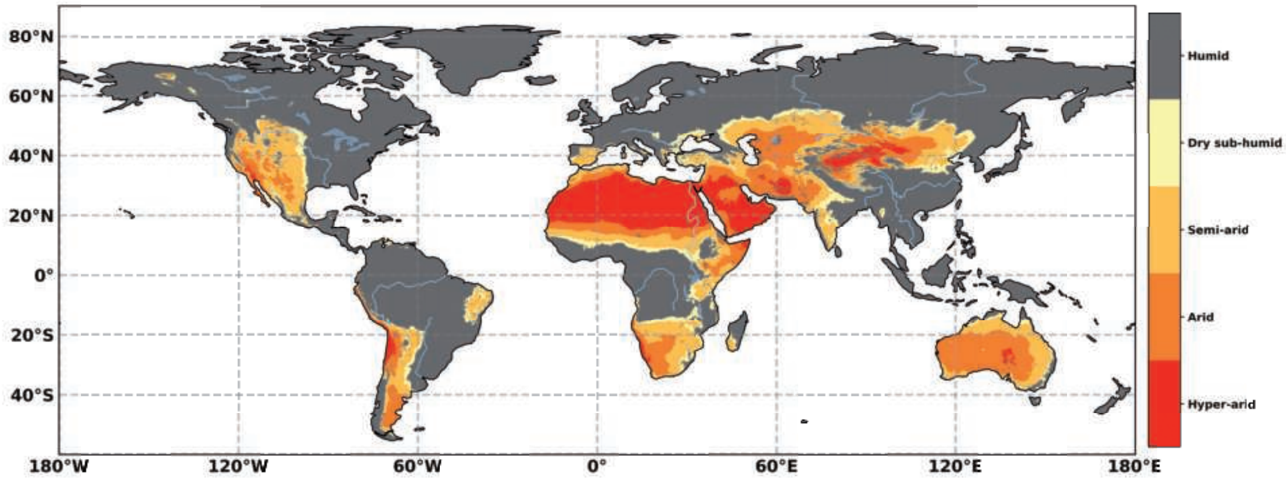


Figure TS.6 | Geographical distribution of drylands, delimited based on the aridity index (AI). The classification of AI is: Humid AI > 0.65, Dry sub-humid 0.50 < AI ≤ 0.65, Semi-arid 0.20 < AI ≤ 0.50, Arid 0.05 < AI ≤ 0.20, Hyper-arid AI < 0.05. Data: TerraClimate precipitation and potential evapotranspiration (1980–2015) (Abatzoglou et al. 2018).

albedo, decreasing the 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*). {3.3.3, 3.4.1, 3.5.2}

Site and regionally-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 with mitigation co-benefits (*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-resilient econogically appropriate plants, 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 and 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 native and other climate resilient tree species (*high confidence*). {3.4.2, 3.6.1, 3.7.2}

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 3 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*). {3.6.3}

Indigenous and local knowledge often contributes 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*). {3.1.3, 3.6.1, 3.6.2}

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 eradication and food security among dryland populations (*high confidence*). Implementation of Land Degradation Neutrality (LDN) policies allows populations to avoid, reduce and reverse desertification, thus contributing to climate change adaptation with mitigation co-benefits (*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*). Developing, enabling and promoting access to cleaner energy sources and technologies 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 proactive drought preparedness and drought risk mitigation are more efficient in limiting drought-caused damages than reactive drought relief efforts (*high confidence*). {3.4.2, 3.6.2, 3.6.3, Cross-Chapter Box 5 in Chapter 3}

The knowledge on limits of adaptation to the 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. They also arise from 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*) Even when solutions are available, social, economic and institutional constraints could pose barriers to their implementation (*medium confidence*) {3.6.4}.

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 showing that every USD invested in strengthening hydro-meteorological and early warning services in developing countries can yield between 4 and 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 LDN (*high confidence*). Expanded use of remotely sensed information for data collection helps in measuring progress towards achieving LDN (*low evidence, high agreement*). {3.2.1, 3.6.2, 3.6.3, Cross-Chapter Box 5 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 that occurs in forest land. Deforestation is the conversion of forest to non-forest land and can result in land degradation. {4.1.3}

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*). {4.1.6, 4.2.1, 4.2.3, 4.3, 4.6.1, 4.7, 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*). In some areas sea level rise has exacerbated coastal erosion (*medium confidence*). Global warming beyond 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 where 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*). {4.2.1, 4.2.2, 4.2.3, 4.4.1, 4.4.2, 4.9.6, 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 be about 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 workload 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 the risk 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*). {4.1.6, 4.2.1, 4.7}

Land degradation is a driver of climate change through emission of greenhouse gases (GHGs) 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 GHGs (*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 GHGs and the reduction in land carbon sinks following deforestation (*high confidence*). Agricultural practices also emit non-CO_2 GHGs 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 GHG 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. {4.2.2, 4.3, 4.5.4, 4.6}

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, for example, through 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 10–60 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. {4.1.6, 4.4.2, 4.5, 4.7.1, 4.8.1, 4.8.3, 4.8.4, 4.9.3}

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 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*). {4.1.6, 4.5.4}

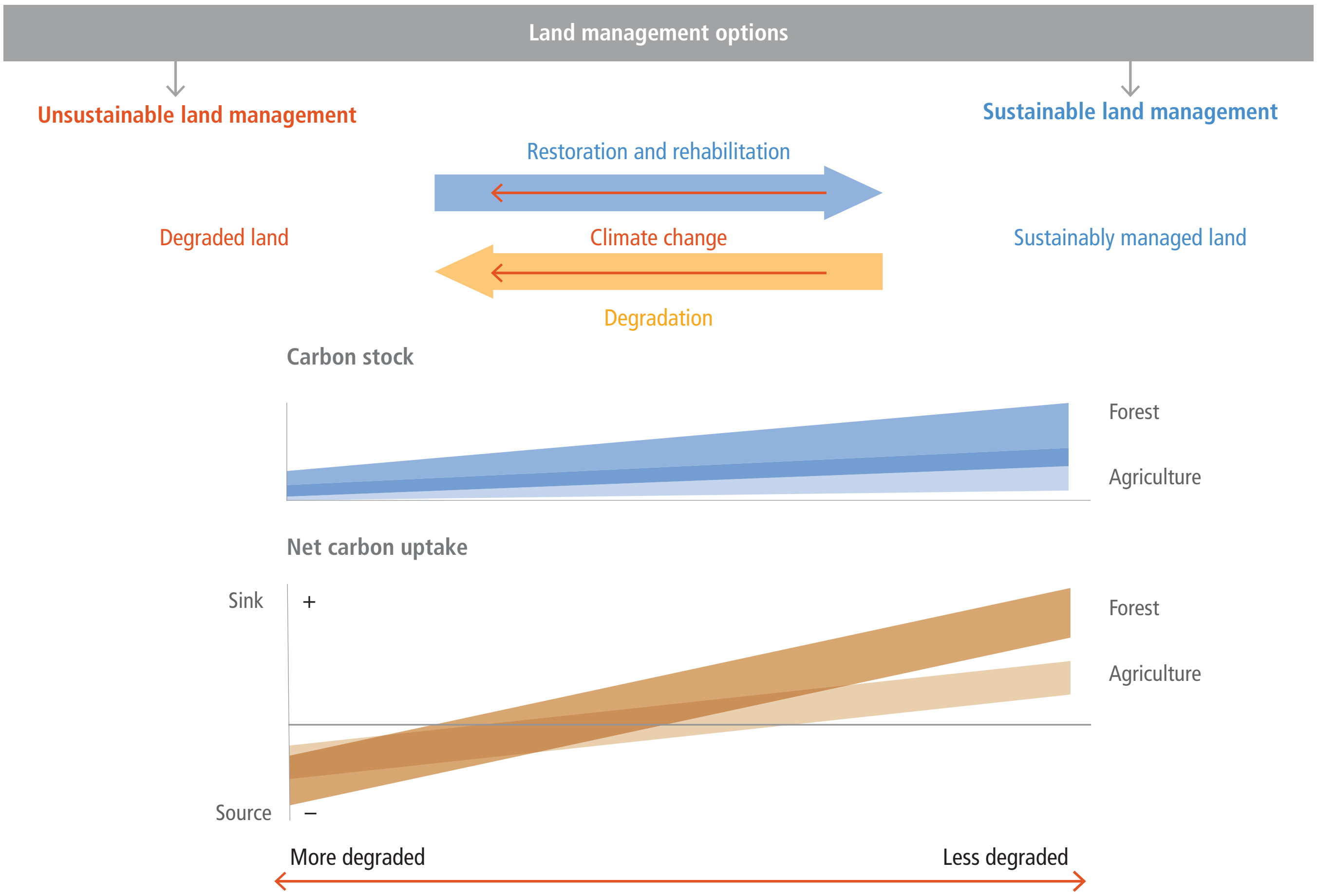


Figure TS.7 | Conceptual figure illustrating that climate change impacts interact with land management to determine sustainable or degraded outcome. Climate change can exacerbate many degradation processes (Table 4.1) and introduce novel ones (e.g., permafrost thawing or biome shifts), hence management 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.

Issue/ syndrome	Impact on climate change	Human driver	Climate driver	Land management options	References
Erosion of agricultural soils	Emission: CO_2, N_2O			Increase soil organic matter, no-till, perennial crops, erosion control, agroforestry, dietary change	3.1.4, 3.4.1, 3.5.2, 3.7.1, 4.8.1, 4.8.5, 4.9.2, 4.9.5
Deforestation	Emission of CO_2			Forest protection, sustainable forest management and dietary change	4.1.5, 4.5, 4.8.3, 4.8.4, 4.9.3
Forest degradation	Emission of CO_2 Reduced carbon sink			Forest protection, sustainable forest management	4.1.5, 4.5, 4.8.3, 4.8.4, 4.9.3
Overgrazing	Emission: CO_2, CH_4 Increasing albedo			Controlled grazing, rangeland management	3.1.4.2, 3.4.1, 3.6.1, 3.7.1, 4.8.1.4
Firewood and charcoal production	Emission: CO_2, CH_4 Increasing albedo			Clean cooking (health co-benefits, particularly for women and children)	3.6.3, 4.5.4, 4.8.3, 4.8.4
Increasing fire frequency and intensity	Emission: CO_2, CH_4, N_2O Emission: aerosols, increasing albedo			Fuel management, fire management	3.1.4, 3.6.1, 4.1.5, 4.8.3, Cross-Chapter Box 3 in Chp 2
Degradation of tropical peat soils	Emission: CO_2, CH_4			Peatland restoration, erosion control, regulating the use of peat soils	4.9.4
Thawing of permafrost	Emission: CO_2, CH_4			Relocation of settlement and infrastructure	4.8.5.1
Coastal erosion	Emission: CO_2, CH_4			Wetland and coastal restoration, mangrove conservation, long-term land-use planning	4 .9.6, 4.9. 7, 4.9.8
Sand and dust storms, wind erosion	Emission: aerosols			Vegetation management, afforestation, windbreaks	3.3.1, 3.4.1, 3.6.1, 3.7.1, 3.7.2
Bush encroachment	Capturing: CO_2, Decreasing albedo			Grazing land management, fire management	3.6.1.3, 3.7.3.2

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

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. 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 GHG emissions, reduced rates of carbon uptake, and reduced capacity of ecosystems to act as carbon sinks into the future. Impacts on climate change are either warming (in red) or cooling (in blue).

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 involves 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 GHG emissions-reduction goals. Sustainable forest management generates socio-economic benefits, and provides fibre, 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 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) {4.8, 4.9, Table 4.2}

Lack of action to address land degradation will increase emissions and reduce carbon sinks and is inconsistent with the emissions 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.7) {4.1.5, 4.1.6, 4.7.1, 4.8, Table 4.2}

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 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. {4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8}

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 – along with 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 existing scientific and locally based approaches, including the use of ILK, 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 waterlogging. 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. {4.10}

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 over 1 billion 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 five 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.9) {5.1.1, 5.1.2}

Observed climate change is already affecting food security through increasing temperatures, changing precipitation patterns, and greater frequency of some extreme events (*high confidence*). Studies that separate out climate change from other factors affecting crop yields have shown that yields of some crops (e.g., maize and wheat) in many lower-latitude regions have been affected negatively by observed climate changes, while in many higher-latitude regions, yields of some crops (e.g., maize, wheat, and sugar beets) have been affected positively over recent decades. Warming compounded by drying has caused large negative effects on yields in parts of the Mediterranean. Based on ILK, climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America. (Figure TS.10) {5.2.2}

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 agropastoralists. Impacts in pastoral systems in Africa include lower pasture and animal productivity, damaged reproductive function, and biodiversity loss. Pastoral system vulnerability is exacerbated by non-climate factors

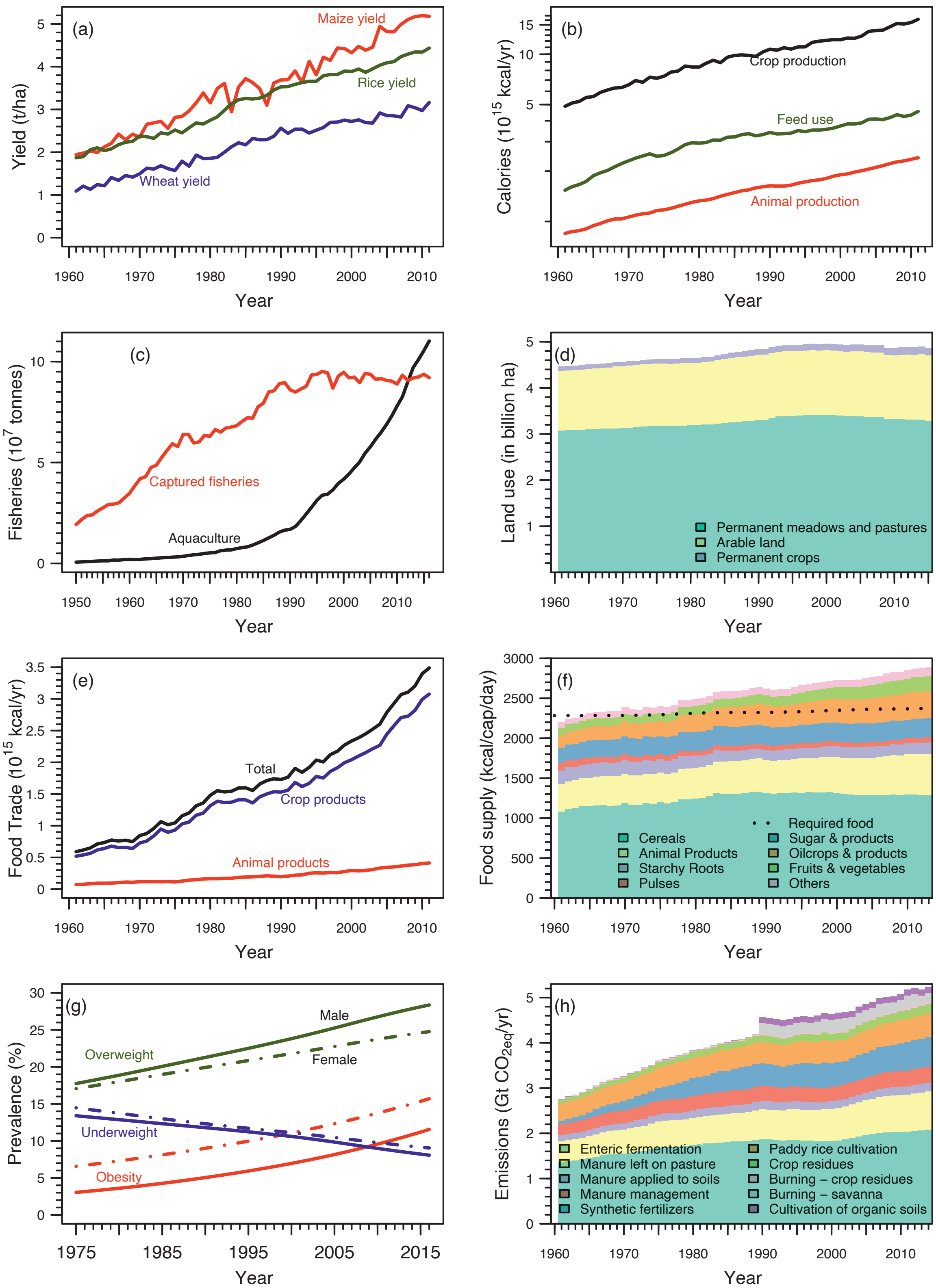


Figure TS.9 | Global trends in (a) yields of maize, rice, and wheat (FAOSTAT 2018) – the top three crops grown in the world; **(b)** production of crop and animal calories and use of crop calories as livestock feed (FAOSTAT 2018); **(c)** production from marine and aquaculture fisheries (FishStat 2019); **(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 requirements for medium physical activities) from 1961–2012 (FAOSTAT 2018; 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).

(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*). Empowering women and rights-based approaches to decision-making can create synergies among household food security, adaptation, and mitigation. {5.2.6, 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, 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. ILK can contribute to enhancing food system resilience (*high confidence*). {5.3, 5.6.3 Cross-Chapter Box 6 in Chapter 5}.

About 21–37% of total greenhouse gas (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 9–14% from crop and livestock activities within the farm gate and 5–14% 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 ± 42 $TgCH_4$ yr^{-1} (*high confidence*) and 8.0 ± 2.5 TgN_2O yr^{-1} (high confidence), and CO_2 emissions linked to relevant land-use change dynamics such as deforestation and peatland degradation, generating 4.9 ± 2.5 $GtCO_2$ 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 ± 1.4 $GtCO_2$-eq yr^{-1}, increasing to 11.1 ± 2.9 $GtCO_2$-eq 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 technical mitigation potential from crop and livestock activities and agroforestry is estimated as 2.3–9.6 $GtCO_2$-eq yr^{-1} by 2050 (*medium 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 technical mitigation potential of dietary changes is estimated as 0.7–8.0 $GtCO_2$-eq yr^{-1} by 2050 (*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 25–30% of total food produced (*medium confidence*). During 2010–2016, global food loss and waste equalled 8–10% of total anthropogenic GHG emissions (*medium confidence*); and cost about 1 trillion USD2012 per year (*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}

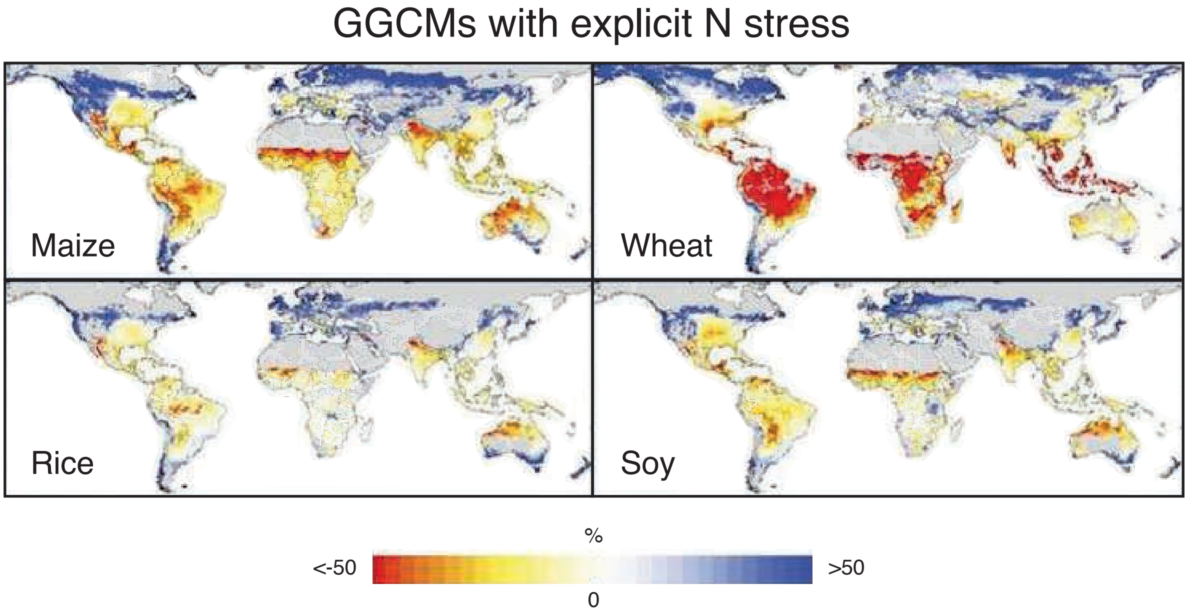


Figure TS.10 | AgMIP median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects and explicit nitrogen stress over five GCMs x four Global Gridded Crop Models (GGCMs) for rainfed maize, wheat, rice, and soy (20 ensemble members from EPIC, GEPIC, pDSSAT, and PEGASUS; except for rice which has 15). Grey 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).

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 numbers of malnourished people and impacts on smallholder farmers (*medium evidence, high agreement*). Just transitions are needed to address these effects. (Figure TS.11) {5.5, 5.6, 5.7}

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 healthcare 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 Chapter 5 will not be realised and food security will be jeopardised (*high confidence*). {5.7.5}

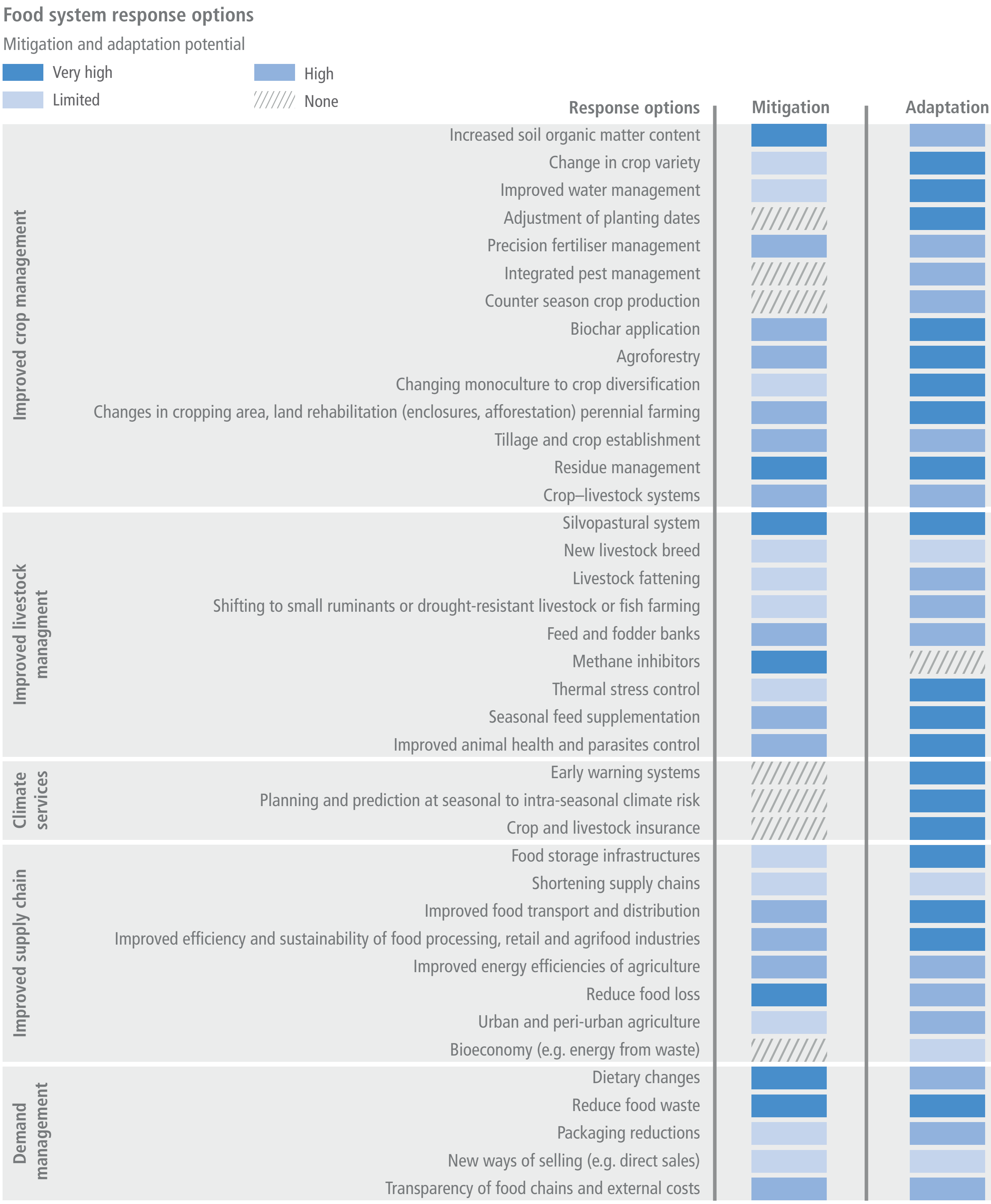


Figure TS.11 | Response options related to food system and their potential impacts on mitigation and adaptation. Many response options offer significant potential for both mitigation and adaptation.

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 socio-economic 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 socio-economic 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*). {6.1}

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*). {6.1, 6.2, 6.3, 6.4}

Nine 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 cropland management, improved grazing land management, improved livestock management, agroforestry, forest management, increased soil organic carbon content, fire management and reduced post-harvest losses. A further two options, dietary change and reduced food waste, have no global estimates for adaptation but have medium-to-large benefits for all other challenges (*high confidence*). {6.3, 6.4}

Five options have large mitigation potential (>3 $GtCO_2e\ yr^{-1}$) without adverse impacts on the other challenges (*high confidence*). These are: increased food productivity; reduced deforestation and forest degradation; increased soil organic carbon content; fire management; and reduced post-harvest losses. Two further options with large mitigation potential, dietary change and reduced food waste, have no global estimates for adaptation but show no negative impacts across the other challenges. Five options: improved cropland management; improved grazing land managements; agroforestry; integrated water management; and forest management, have moderate mitigation potential, with no adverse impacts on the other challenges (*high confidence*). {6.3.6}

Sixteen response options have large adaptation potential (more than 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, 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) {6.3, 6.4}

Seventeen of 40 options deliver co-benefits or no adverse side effects for the full range of NCPs and SDGs; only three options (afforestation, 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, 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 eradication 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. {6.4}

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 or 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 forest 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*). {6.3.6, 6.4}

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*). {6.2, 6.3, 6.4, Cross-Chapter Box 7 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; about 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. {6.4}

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 (*high confidence*). (Figure TS.12) {6.4}

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*). {6.3, 6.4}

Coordinated action is required across a range of actors, including business, producers, consumers, land managers, indigenous peoples 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 eradication 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*). {6.3, 6.4}

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 forest 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 – such as 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*) {6.2, 6.3, 6.4}.

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, for example, BECCS, have only been implemented at small-scale demonstration facilities; challenges exist with upscaling these options to the levels discussed in Chapter 6 (*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 reducing emissions from deforestation and forest degradation and fostering conservation (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. {6.2, 6.4}

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 socio-economic 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*). {6.4}

Many response options have been practised 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 the IPCC Special Report on Global Warming of 1.5°C (SR15), omit many of these response options and do not assess implications for all land challenges (*high confidence*). {6.4}

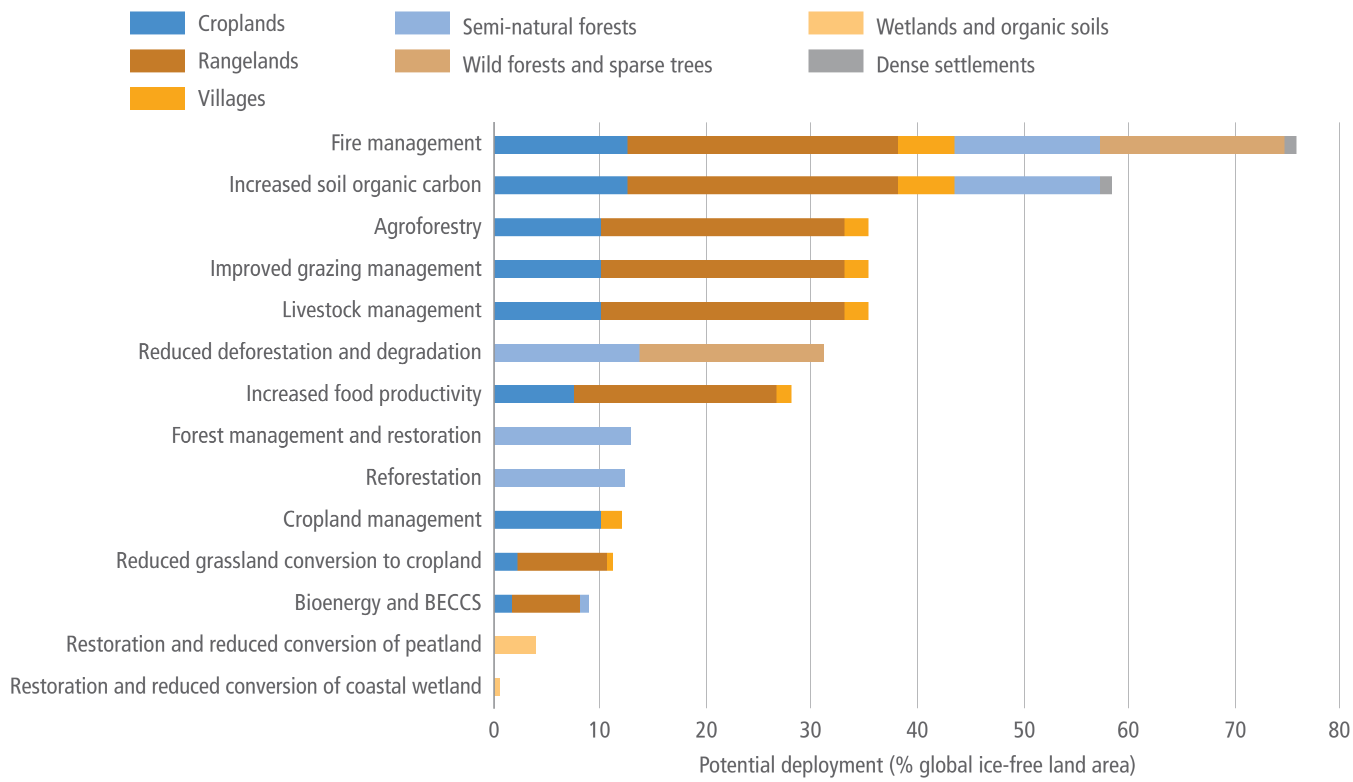


Figure TS.12 | Potential deployment area of land management responses (see Table 6.1) across land-use types (or anthromes, see Section 6.3), when selecting responses having only co-benefits for local challenges and for climate change mitigation and no large adverse side effects on global food security. See Figure 6.2 for the criteria used to map challenges considered (desertification, land degradation, climate change adaptation, chronic undernourishment, biodiversity, groundwater stress and water quality). No response option was identified for barren lands.

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel A shows response options that can be implemented without or with limited competition for land, including some that have the potential to reduce the demand for land. Co-benefits and adverse side effects are shown quantitatively based on the high end of the range of potentials assessed. Magnitudes of contributions are categorised using thresholds for positive or negative impacts. Letters within the cells indicate confidence in the magnitude of the impact relative to the thresholds used (see legend). Confidence in the direction of change is generally higher.

Response options based on land management

	Response option	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Agriculture	Increased food productivity	L (Large)	M (Large)	L (Large)	M (Large)	H (Large)	—
Agriculture	Agro-forestry	M (Large)	M (Large)	M (Large)	M (Large)	L (Large)	●
Agriculture	Improved cropland management	M (Moderate)	L (Large)	L (Large)	L (Large)	L (Large)	●●
Agriculture	Improved livestock management	M (Moderate)	L (Moderate)	L (Moderate)	L (Large)	L (Large)	●●●
Agriculture	Agricultural diversification	L (Small)	L (Large)	L (Moderate)	M (Large)	L (Large)	●
Agriculture	Improved grazing land management	M (Moderate)	L (Moderate)	L (Moderate)	L (Large)	L (Large)	—
Agriculture	Integrated water management	L (Moderate)	L (Large)	L (Small)	L (Small)	L (Large)	●●
Agriculture	Reduced grassland conversion to cropland	L (Moderate)	—	L (Small)	L (Small)	- L (Moderate negative)	●
Forests	Forest management	M (Moderate)	L (Large)	L (Large)	L (Large)	L (Moderate)	●●
Forests	Reduced deforestation and forest degradation	H (Large)	L (Moderate)	L (Large)	L (Large)	L (Small)	●●
Soils	Increased soil organic carbon content	H (Large)	L (Large)	M (Large)	M (Large)	L (Large)	●●
Soils	Reduced soil erosion	↔ L	L (Large)	M (Large)	M (Large)	L (Large)	●●
Soils	Reduced soil salinization	—	L (Moderate)	L (Moderate)	L (Moderate)	L (Moderate)	●●
Soils	Reduced soil compaction	—	L (Small)	—	L (Large)	L (Moderate)	●
Other ecosystems	Fire management	M (Large)	M (Moderate)	M (Large)	M (Large)	L (Moderate)	●
Other ecosystems	Reduced landslides and natural hazards	L (Small)	L (Large)	L (Small)	L (Large)	L (Moderate)	—
Other ecosystems	Reduced pollution including acidification	↔ M	M (Moderate)	L (Moderate)	L (Moderate)	L (Large)	—
Other ecosystems	Restoration & reduced conversion of coastal wetlands	M (Large)	L (Large)	M (Negligible)	M (Small)	↔ L	—
Other ecosystems	Restoration & reduced conversion of peatlands	M (Moderate)	—	na	M (Moderate)	- L (Moderate negative)	●

Response options based on value chain management

	Response option	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Demand	Reduced post-harvest losses	H (Large)	M (Large)	L (Moderate)	L (Moderate)	H (Large)	—
Demand	Dietary change	H (Large)	—	L (Moderate)	H (Large)	H (Large)	—
Demand	Reduced food waste (consumer or retailer)	H (Large)	—	L (Moderate)	M (Large)	M (Large)	—
Supply	Sustainable sourcing	—	L (Moderate)	—	L (Large)	L (Moderate)	—
Supply	Improved food processing and retailing	L (Moderate)	L (Large)	—	—	L (Large)	—
Supply	Improved energy use in food systems	L (Moderate)	L (Large)	—	—	L (Large)	—

Response options based on risk management

	Response option	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Risk	Livelihood diversification	—	L (Large)	—	L (Small)	L (Large)	—
Risk	Management of urban sprawl	—	L (Moderate)	L (Small)	M (Small)	L (Moderate)	—
Risk	Risk sharing instruments	↔ L	L (Moderate)	—	↔ L	L (Moderate)	●●

Options shown are those for which data are available to assess global potential for three or more land challenges.
The magnitudes are assessed independently for each option and are not additive.

Key for criteria used to define magnitude of impact of each integrated response option

		Mitigation *Gt CO₂-eq yr⁻¹*	Adaptation *Million people*	Desertification *Million km²*	Land Degradation *Million km²*	Food Security *Million people*
Positive	Large	More than 3	Positive for more than 25	Positive for more than 3	Positive for more than 3	Positive for more than 100
Positive	Moderate	0.3 to 3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
Positive	Small	Less than 0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	Negligible	No effect	No effect	No effect	No effect	No effect
Negative	Small	Less than -0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
Negative	Moderate	-0.3 to -3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
Negative	Large	More than -3	Negative for more than 25	Negative for more than 3	Negative for more than 3	Negative for more than 100

↔ **Variable:** Can be positive or negative — no data na not applicable

Confidence level

Indicates confidence in the estimate of magnitude category.

H High confidence
M Medium confidence
L Low confidence

Cost range

See technical caption for cost ranges in US\$ tCO_2e^{-1} or US\$ ha^{-1}.

●●● High cost
●● Medium cost
● Low cost
— no data

Figure TS.13 | Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security (Panel A).

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel B shows response options that rely on additional land-use change and could have implications across three or more land challenges under different implementation contexts. For each option, the first row (high level implementation) shows a quantitative assessment (as in Panel A) of implications for global implementation at scales delivering CO_2 removals of more than 3 $GtCO_2\ yr^{-1}$ using the magnitude thresholds shown in Panel A. The red hatched cells indicate an increasing pressure but unquantified impact. For each option, the second row (best practice implementation) shows qualitative estimates of impact if implemented using best practices in appropriately managed landscape systems that allow for efficient and sustainable resource use and supported by appropriate governance mechanisms. In these qualitative assessments, green indicates a positive impact, grey indicates a neutral interaction.

Bioenergy and BECCS

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
H	L			L	● / ●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts, assuming carbon dioxide removal by BECCS at a scale of 11.3 $GtCO_2\ yr^{-1}$ in 2050, and noting that bioenergy without CCS can also achieve emissions reductions of up to several $GtCO_2\ yr^{-1}$ when it is a low carbon energy source {2.6.1; 6.3.1}. Studies linking bioenergy to food security estimate an increase in the population at risk of hunger to up to 150 million people at this level of implementation {6.3.5}. The red hatched cells for desertification and land degradation indicate that while up to 15 million km^2 of additional land is required in 2100 in 2°C scenarios which will increase pressure for desertification and land degradation, the actual area affected by this additional pressure is not easily quantified {6.3.3; 6.3.4}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: The sign and magnitude of the effects of bioenergy and BECCS depends on the scale of deployment, the type of bioenergy feedstock, which other response options are included, and where bioenergy is grown (including prior land use and indirect land use change emissions). For example, limiting bioenergy production to marginal lands or abandoned cropland would have negligible effects on biodiversity, food security, and potentially co-benefits for land degradation; however, the benefits for mitigation could also be smaller. {Table 6.58}

Reforestation and forest restoration

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	M	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of reforestation and forest restoration (partly overlapping with afforestation) at a scale of 10.1 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people; the impact of reforestation is lower {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: There are co-benefits of reforestation and forest restoration in previously forested areas, assuming small scale deployment using native species and involving local stakeholders to provide a safety net for food security. Examples of sustainable implementation include, but are not limited to, reducing illegal logging and halting illegal forest loss in protected areas, reforesting and restoring forests in degraded and desertified lands {Box6.1C; Table 6.6}.

Afforestation

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	L	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of afforestation (partly overlapping with reforestation and forest restoration) at a scale of 8.9 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: Afforestation is used to prevent desertification and to tackle land degradation. Forested land also offers benefits in terms of food supply, especially when forest is established on degraded land, mangroves, and other land that cannot be used for agriculture. For example, food from forests represents a safety-net during times of food and income insecurity {6.3.5}.

Biochar addition to soil

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	—	—	L	L	●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of biochar at a scale of 6.6 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Dedicated biomass crops required for feedstock production could occupy 0.4–2.6 Mkm^2 of land, equivalent to around 20% of the global cropland area, which could potentially have a large effect on food security for up to 100 million people {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: When applied to land, biochar could provide moderate benefits for food security by improving yields by 25% in the tropics, but with more limited impacts in temperate regions, or through improved water holding capacity and nutrient use efficiency. Abandoned cropland could be used to supply biomass for biochar, thus avoiding competition with food production; 5–9 Mkm^2 of land is estimated to be available for biomass production without compromising food security and biodiversity, considering marginal and degraded land and land released by pasture intensification {6.3.5}.

Figure TS.13 | Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security (Panel B).

Figure TS.13 (continued): This Figure is based on an aggregation of information from studies with a wide variety of assumptions about how response options are implemented and the contexts in which they occur. Response options implemented differently at local to global scales could lead to different outcomes. **Magnitude of potential:** For panel A, magnitudes are for the technical potential of response options globally. For each land challenge, magnitudes are set relative to a marker level as follows. For mitigation, potentials are set relative to the approximate potentials for the response options with the largest individual impacts (~3 $GtCO_2$-eq yr^{-1}). The threshold for the 'large' magnitude category is set at this level. For adaptation, magnitudes are set relative to the 100 million lives estimated to be affected by climate change and a carbon-based economy between 2010 and 2030. The threshold for the 'large' magnitude category represents 25% of this total. For desertification and land degradation, magnitudes are set relative to the lower end of current estimates of degraded land, 10–60 million km^2. The threshold for the 'large' magnitude category represents 30% of the lower estimate. For food security, magnitudes are set relative to the approximately 800 million people who are currently undernourished. The threshold for the 'large' magnitude category represents 12.5% of this total. For panel B, for the first row (high level implementation) for each response option, the magnitude and thresholds are as defined for panel A. In the second row (best practice implementation) for each response option, the qualitative assessments that are green denote potential positive impacts, and those shown in grey indicate neutral interactions. Increased food production is assumed to be achieved through sustainable intensification rather than through injudicious application of additional external inputs such as agrochemicals. **Levels of confidence:** Confidence in the magnitude category (high, medium or low) into which each option falls for mitigation, adaptation, combating desertification and land degradation, and enhancing food security. *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:** Cost estimates are based on aggregation of often regional studies and vary in the components of costs that are included. In panel B, cost estimates are not provided for best practice implementation. One coin indicates low cost (<USD10 tCO_2-eq^{-1} or <USD20 ha^{-1}), two coins indicate medium cost (USD10–USD100 tCO_2-eq^{-1} or USD20–USD200 ha^{-1}), and three coins indicate high cost (>USD100 tCO_2-eq^{-1} or USD200 ha^{-1}). Thresholds in USD 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 quantitative potential for land management-based response options can be found as follows: for mitigation Tables 6.13 to 6.20, with further evidence in Section 2.7.1; 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 Table's 6.45 to 6.52, with further evidence in Chapter 5. Other synergies and trade-offs not shown here are discussed in Chapter 6. Additional supporting evidence for the qualitative assessments in the second row for each option in panel B can be found in the Table's 6.6, 6.55, 6.56 and 6.58, Section 6.3.5.1.3, and Box 6.1c.

TS.7 Risk management and decision making in relation 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*). {7.2.2.1, 7.2.2.2, 7.2.2.3; 7.2.2.4; 7.2.2.5; 7.2.2.6; 7.2.2.7; Figure 7.1}

These changes result in compound risks to food systems, human and ecosystem health, livelihoods, the viability of infrastructure, and the value of land (*high confidence*). The experience and dynamics of risk change over time as a result of both human and natural processes (*high confidence*). There is *high confidence* that climate and land changes pose increased risks at certain periods of life (i.e. to the very young and ageing populations) as well as sustained risk to those living in poverty. Response options may also increase risks. For example, domestic efforts to insulate populations from food price spikes associated with climatic stressors in the mid-2000s inadequately prevented food insecurity and poverty, and worsened poverty globally. (Figure TS.14) {7.2.1, 7.2.2, 7.3, Table 7.1}

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

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

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

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

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

Trade-offs can occur between using land for climate mitigation or Sustainable Development Goal (SDG) 7 (affordable clean energy) with biodiversity, food, groundwater and riverine ecosystem services (*medium confidence*). There is *medium confidence* that trade-offs currently do not figure into climate policies and decision making. Small hydro power installations (especially in clusters) can impact downstream river ecological connectivity for fish (*high agreement, medium evidence*). Large scale solar farms and wind turbine installations can impact endangered species and disrupt habitat connectivity (*medium agreement, medium evidence*). Conversion of rivers for transportation can disrupt fisheries and endangered species (through dredging and traffic) (*medium agreement, low evidence*). {7.5.6}

The full mitigation potential assessed in this report will only be realised if agricultural emissions are included in mainstream climate policy (*high agreement, high evidence*). Carbon markets are theoretically more cost-effective than taxation but challenging to implement in the land-sector (*high confidence*) Carbon pricing (through carbon markets or carbon taxes) has the potential to be an effective mechanism to reduce GHG emissions, although it remains relatively untested in agriculture and food systems. Equity considerations can be balanced by a mix of both market and non-market mechanisms (*medium evidence, medium agreement*). Emissions leakage could be reduced by multi-lateral action (*high agreement, medium evidence*). {7.4.6, 7.5.5, 7.5.6, Cross Chapter Box 9 in 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 (SLM), mitigation, and adaptation are less than the consequences of inaction for humans and ecosystems (*medium confidence*). Policy portfolios that make ecological restoration more attractive, people more resilient – expanding financial inclusion, flexible carbon credits, disaster risk and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems – could save 100 billion USD a year, if implemented globally. {7.3.1, 7.4.7, 7.4.8, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

Coordination of policy instruments across scales, levels, and sectors advances co-benefits, manages land and climate risks, advances food security, and addresses equity concerns (*medium confidence*). Flood resilience policies are mutually reinforcing and include flood zone mapping, financial incentives to move, and building restrictions, and insurance. Sustainability certification, technology transfer, land-use standards and secure land tenure schemes, integrated with early action and preparedness, advance response options. SLM improves with investment in agricultural research, environmental farm practices, agri-environmental payments, financial support for sustainable agricultural water infrastructure (including dugouts), agriculture emission trading, and elimination of agricultural subsidies (*medium confidence*). Drought resilience policies (including drought preparedness planning, early warning and monitoring, improving water use efficiency), synergistically improve agricultural producer livelihoods and foster SLM. (Figure TS.15) {3.7.5, Cross-Chapter Box 5 in Chapter 3, 7.4.3, 7.4.6, 7.5.6, 7.4.8, 7.5.6, 7.6.3}

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

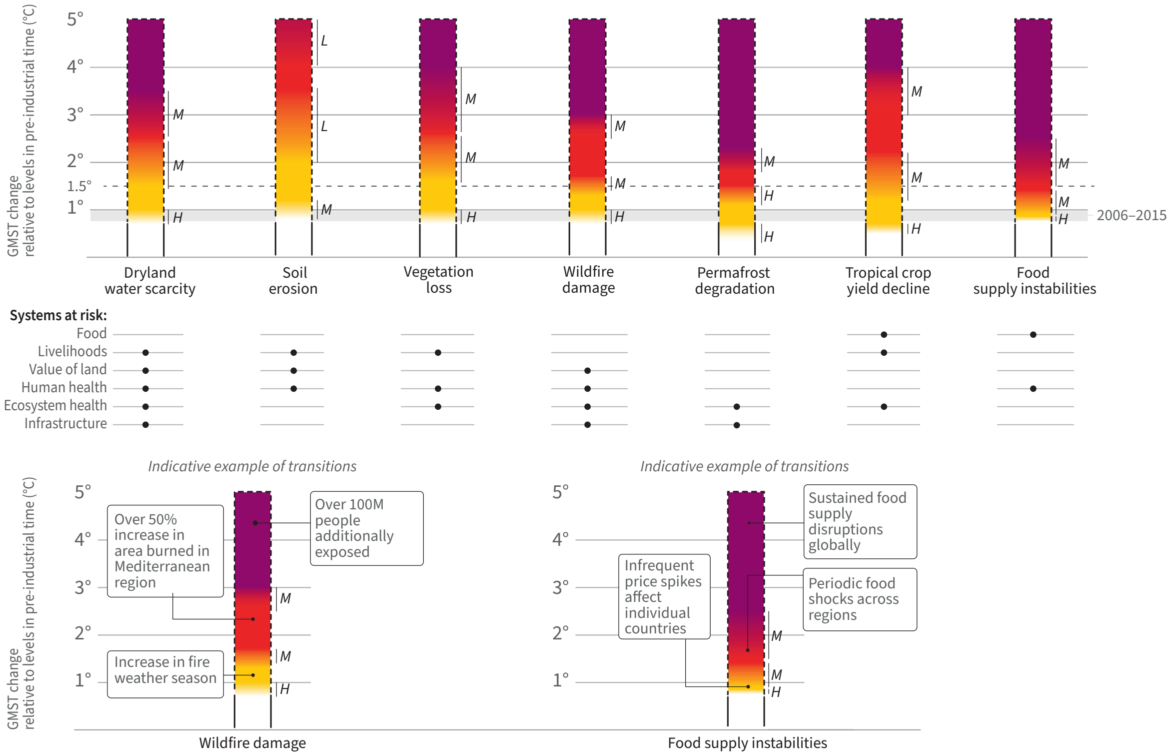
Measuring progress towards goals is important in decision-making and adaptive governance to create common understanding and advance policy effectiveness (*high agreement, medium evidence*). Measurable indicators, selected with the participation of people and supporting data collection, are useful for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

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

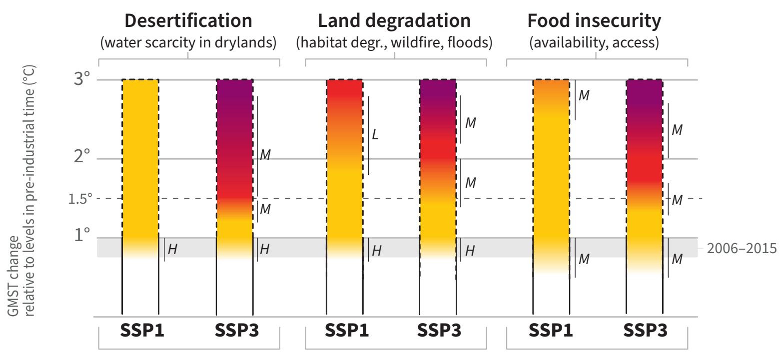
ILK can play a key role in understanding climate processes and impacts, adaptation to climate change, SLM across different ecosystems, and enhancement of food security (*high confidence*). ILK is context-specific, collective, informally transmitted, and multi-functional, and can encompass factual information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

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

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



B. Different socioeconomic pathways affect levels of climate related risks



Socio-economic choices can reduce or exacerbate climate related risks as well as influence the rate of temperature increase. The **SSP1** pathway illustrates a world with low population growth, high income and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity. The **SSP3** pathway has the opposite trends. Risks are lower in SSP1 compared with SSP3 given the same level of GMST increase.

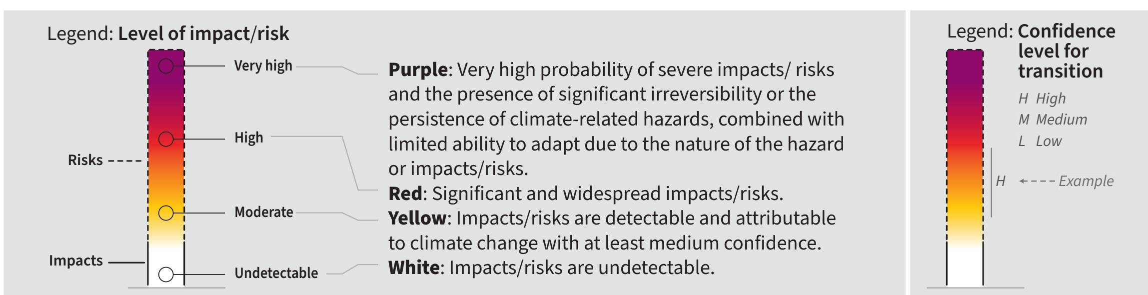


Figure TS.14 | Risks to land-related human systems and ecosystems from global climate change, socio-economic development and mitigation choices.

Figure TS.14 (continued): As in previous IPCC reports the literature was used to make expert judgements to assess the levels of global warming at which levels of risk are undetectable, moderate, high or very high, as described further in Chapter 7 and other parts of the underlying report. The figure indicates assessed risks at approximate warming levels which may be influenced by a variety of factors, including adaptation responses. The assessment considers adaptive capacity consistent with the SSP pathways as described below. **Panel A:** Risks to selected elements of the land system as a function of global mean surface temperature {2.1; Box 2.1; 3.5; 3.7.1.1; 4.4.1.1; 4.4.1.2; 4.4.1.3; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 7.2;7.3, Table SM7.1}. Links to broader systems are illustrative and not intended to be comprehensive. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway. {Table SM7.4}. **Panel B:** Risks associated with desertification, land degradation and food security due to climate change and patterns of socio-economic development. Increasing risks associated with desertification include population exposed and vulnerable to water scarcity in drylands. Risks related to land degradation include increased habitat degradation, population exposed to wildfire and floods and costs of floods. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable due to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3 {SPM Box 1}) excluding the effects of targeted mitigation policies {3.5; 4.2.1.2; 5.2.2; 5.2.3; 5.2.4; 5.2.5; 6.1.4; 7.2, Table SM7.5}. Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change. All panels: As part of the assessment, literature was compiled and data extracted into a summary table. A formal expert elicitation protocol (based on modified-Delphi technique and the Sheffield Elicitation Framework), was followed to identify risk transition thresholds. This included a multi-round elicitation process with two rounds of independent anonymous threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 7 Supplementary Material.

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 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 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}

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

Category	Intergrated Response Option	Policy instrument supporting response option
Land management in agriculture	Increased food productivity	Investment in agricultural research for crop and livestock improvement, agricultural technology transfer, inland capture fisheries and aquaculture {7.4.7} agricultural policy reform and trade liberalisation
	Improved cropland, grazing and livestock management	Environmental farm programs/agri-environment schemes, water efficiency requirements and water transfer {3.8.5}, extension services
	Agroforestry	Payment for ecosystem services (ES) {7.4.6}
	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 {7.4.6}
	Integrated water management	Integrated governance {7.6.2}, multi-level instruments [7.4.1}
Land management in forests	Forest management, reduced deforestation and degradation, reforestation and forest restoration, afforestation	REDD+, forest conservation regulations, payments for ES, recognition of forest rights and land tenure {7.4.6}, adaptive management of forests {7.5.4}, land-use moratoriums, reforestation programmes and investment {4.9.1}
Land management of soils	Increased soil organic carbon content, reduced soil erosion, reduced soil salinisation, reduced soil compaction, biochar addition to soil	Land degradation neutrality (LDN) {7.4.5}, drought plans, flood plans, flood zone mapping {7.4.3}, technology transfer (7.4.4}, land-use zoning {7.4.6}, ecological service mapping and stakeholder-based quantification {7.5.3}, environmental farm programmes/agri-environment schemes, water-efficiency requirements and water transfer {3.7.5}
Land management in all other ecosystems	Fire management	Fire suppression, prescribed fire management, mechanical treatments {7.4.3}
	Reduced landslides and natural hazards	Land-use zoning {7.4.6}
	Reduced pollution – acidification	Environmental regulations, climate mitigation (carbon pricing) {7.4.4}
	Management of invasive species/ encroachment	Invasive species regulations, trade regulations {5.7.2, 7.4.6}
	Restoration and reduced conversion of coastal wetlands	Flood zone mapping {7.4.3}, land-use zoning {7.4.6}
	Restoration and reduced conversion of peatlands	Payment for ES {7.4.6; 7.5.3}, standards and certification programmes {7.4.6}, land-use moratoriums
	Biodiversity conservation	Conservation regulations, protected areas policies
Carbon dioxide removal (CDR) land management	Enhanced weathering of minerals	No data
	Bioenergy and bioenergy with carbon capture and storage (BECCS)	Standards and certification for sustainability of biomass and land use {7.4.6}
Demand management	Dietary change	Awareness campaigns/education, changing food choices through nudges, synergies with health insurance and policy {5.7.2}
	Reduced post-harvest losses Reduced food waste (consumer or retailer), material substitution	Agricultural business risk programmes {7.4.8}; regulations to reduce and taxes on food waste, improved shelf life, circularising the economy to produce substitute goods, carbon pricing, sugar/fat taxes {5.7.2}
Supply management	Sustainable sourcing	Food labelling, innovation to switch to food with lower environmental footprint, public procurement policies {5.7.2}, standards and certification programmes {7.4.6}
	Management of supply chains	Liberalised international trade {5.7.2}, food purchasing and storage policies of governments, standards and certification programmes {7.4.6}, regulations on speculation in food systems
	Enhanced urban food systems	Buy local policies; land-use zoning to encourage urban agriculture, nature-based solutions and green infrastructure in cities; incentives for technologies like vertical farming
	Improved food processing and retailing, improved energy use in food systems	Agriculture emission trading {7.4.4}; investment in R&D for new technologies; certification
Risk management	Management of urban sprawl	Land-use zoning {7.4.6}
	Livelihood diversification	Climate-smart agriculture policies, adaptation policies, extension services {7.5.6}
	Disaster risk management	Disaster risk reduction {7.5.4; 7.4.3}, adaptation planning
	Risk-sharing instruments	Insurance, iterative risk management, CAT bonds, risk layering, contingency funds {7.4.3}, agriculture business risk portfolios {7.4.8}

A. Pathways linking socioeconomic development, mitigation responses and land

Socioeconomic development and land management influence the evolution of the land system including the relative amount of land allocated to CROPLAND, PASTURE, BIOENERGY CROPLAND, FOREST, and NATURAL LAND. The lines show the median across Integrated Assessment Models (IAMs) for three alternative shared socioeconomic pathways (**SSP1**, **SSP2** and **SSP5** at **RCP1.9**); shaded areas show the range across models. Note that pathways illustrate the effects of climate change mitigation but not those of climate change impacts or adaptation.

A. Sustainability-focused (SSP1)
Sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation, and bioenergy.

B. Middle of the road (SSP2)
Societal as well as technological development follows historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre.

C. Resource intensive (SSP5)
Resource-intensive production and consumption patterns, results in high baseline emissions. Mitigation focuses on technological solutions including substantial bioenergy and BECCS . Intensification and competing land uses contribute to declines in agricultural land.

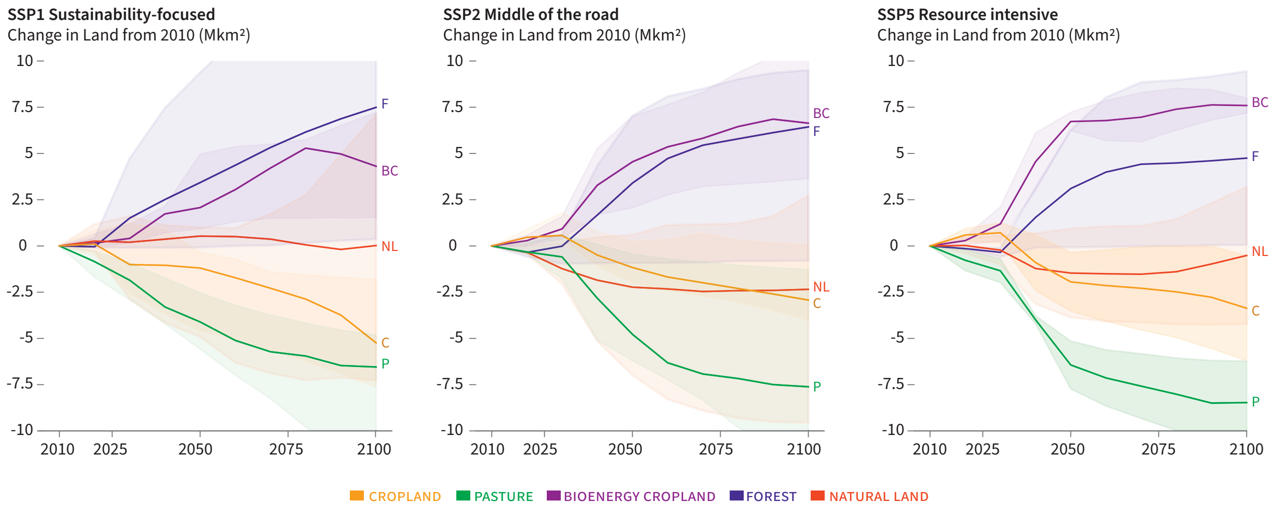


Figure TS.15 | Pathways linking socioeconomic development, mitigation responses and land (Panel A).

B. Land use and land cover change in the SSPs

	Quantitative indicators for the SSPs	Count of models included*	Change in Natural Land from 2010 Mkm²	Change in Bioenergy Cropland from 2010 Mkm²	Change in Cropland from 2010 Mkm²	Change in Forest from 2010 Mkm²	Change in Pasture from 2010 Mkm²
SSP1	**RCP1.9** in 2050	5/5	0.5 (-4.9, 1)	2.1 (0.9, 5)	-1.2 (-4.6, -0.3)	3.4 (-0.1, 9.4)	-4.1 (-5.6, -2.5)
	↳ 2100		0 (-7.3, 7.1)	4.3 (1.5, 7.2)	-5.2 (-7.6, -1.8)	7.5 (0.4, 15.8)	-6.5 (-12.2, -4.8)
	RCP2.6 in 2050	5/5	-0.9 (-2.2, 1.5)	1.3 (0.4, 1.9)	-1 (-4.7, 1)	2.6 (-0.1, 8.4)	-3 (-4, -2.4)
	↳ 2100		0.2 (-3.5, 1.1)	5.1 (1.6, 6.3)	-3.2 (-7.7, -1.8)	6.6 (-0.1, 10.5)	-5.5 (-9.9, -4.2)
	RCP4.5 in 2050	5/5	0.5 (-1, 1.7)	0.8 (0.5, 1.3)	0.1 (-3.2, 1.5)	0.6 (-0.7, 4.2)	-2.4 (-3.3, -0.9)
	↳ 2100		1.8 (-1.7, 6)	1.9 (1.4, 3.7)	-2.3 (-6.4, -1.6)	3.9 (0.2, 8.8)	-4.6 (-7.3, -2.7)
	Baseline in 2050	5/5	0.3 (-1.1, 1.8)	0.5 (0.2, 1.4)	0.2 (-1.6, 1.9)	-0.1 (-0.8, 1.1)	-1.5 (-2.9, -0.2)
	↳ 2100		3.3 (-0.3, 5.9)	1.8 (1.4, 2.4)	-1.5 (-5.7, -0.9)	0.9 (0.3, 3)	-2.1 (-7, 0)
SSP2	**RCP1.9** in 2050	4/5	-2.2 (-7, 0.6)	4.5 (2.1, 7)	-1.2 (-2, 0.3)	3.4 (-0.9, 7)	-4.8 (-6.2, -0.4)
	↳ 2100		-2.3 (-9.6, 2.7)	6.6 (3.6, 11)	-2.9 (-4, 0.1)	6.4 (-0.8, 9.5)	-7.6 (-11.7, -1.3)
	RCP2.6 in 2050	5/5	-3.2 (-4.2, 0.1)	2.2 (1.7, 4.7)	0.6 (-1.9, 1.9)	1.6 (-0.9, 4.2)	-1.4 (-3.7, 0.4)
	↳ 2100		-5.2 (-7.2, 0.5)	6.9 (2.3, 10.8)	-1.4 (-4, 0.8)	5.6 (-0.9, 5.9)	-7.2 (-8, 0.5)
	RCP4.5 in 2050	5/5	-2.2 (-2.2, 0.7)	1.5 (0.1, 2.1)	1.2 (-0.9, 2.7)	-0.9 (-2.5, 2.9)	-0.1 (-2.5, 1.6)
	↳ 2100		-3.4 (-4.7, 1.5)	4.1 (0.4, 6.3)	0.7 (-2.6, 3.1)	-0.5 (-3.1, 5.9)	-2.8 (-5.3, 1.9)
	Baseline in 2050	5/5	-1.5 (-2.6, -0.2)	0.7 (0, 1.5)	1.3 (1, 2.7)	-1.3 (-2.5, -0.4)	-0.1 (-1.2, 1.6)
	↳ 2100		-2.1 (-5.9, 0.3)	1.2 (0.1, 2.4)	1.9 (0.8, 2.8)	-1.3 (-2.7, -0.2)	-0.2 (-1.9, 2.1)
SSP3	**RCP1.9** in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP4.5 in 2050	3/3	-3.4 (-4.4, -2)	1.3 (1.3, 2)	2.3 (1.2, 3)	-2.4 (-4, -1)	2.1 (-0.1, 3.8)
	↳ 2100		-6.2 (-6.8, -5.4)	4.6 (1.5, 7.1)	3.4 (1.9, 4.5)	-3.1 (-5.5, -0.3)	2 (-2.5, 4.4)
	Baseline in 2050	4/4	-3 (-4.6, -1.7)	1 (0.2, 1.5)	2.5 (1.5, 3)	-2.5 (-4, -1.5)	2.4 (0.6, 3.8)
	↳ 2100		-5 (-7.1, -4.2)	1.1 (0.9, 2.5)	5.1 (3.8, 6.1)	-5.3 (-6, -2.6)	3.4 (0.9, 6.4)
SSP4	**RCP1.9** in 2050	Infeasible in all assessed models**		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	3/3	-4.5 (-6, -2.1)	3.3 (1.5, 4.5)	0.5 (-0.1, 0.9)	0.7 (-0.3, 2.2)	-0.6 (-0.7, 0.1)
	↳ 2100		-5.8 (-10.2, -4.7)	2.5 (2.3, 15.2)	-0.8 (-0.8, 1.8)	1.4 (-1.7, 4.1)	-1.2 (-2.5, -0.2)
	RCP4.5 in 2050	3/3	-2.7 (-4.4, -0.4)	1.7 (1, 1.9)	1.1 (-0.1, 1.7)	-1.8 (-2.3, 2.1)	0.8 (-0.5, 1.5)
	↳ 2100		-2.8 (-7.8, -2)	2.7 (2.3, 4.7)	1.1 (0.2, 1.2)	-0.7 (-2.6, 1)	1.4 (-1, 1.8)
	Baseline in 2050	3/3	-2.8 (-2.9, -0.2)	1.1 (0.7, 2)	1.1 (0.7, 1.8)	-1.8 (-2.3, -1)	1.5 (-0.5, 2.1)
	↳ 2100		-2.4 (-5, -1)	1.7 (1.4, 2.6)	1.2 (1.2, 1.9)	-2.4 (-2.5, -2)	1.3 (-1, 4.4)
SSP5	**RCP1.9** in 2050	2/4	-1.5 (-3.9, 0.9)	6.7 (6.2, 7.2)	-1.9 (-3.5, -0.4)	3.1 (-0.1, 6.3)	-6.4 (-7.7, -5.1)
	↳ 2100		-0.5 (-4.2, 3.2)	7.6 (7.2, 8)	-3.4 (-6.2, -0.5)	4.7 (0.1, 9.4)	-8.5 (-10.7, -6.2)
	RCP2.6 in 2050	4/4	-3.4 (-6.9, 0.3)	4.8 (3.8, 5.1)	-2.1 (-4, 1)	3.9 (-0.1, 6.7)	-4.4 (-5, 0.2)
	↳ 2100		-4.3 (-8.4, 0.5)	9.1 (7.7, 9.2)	-3.3 (-6.5, -0.5)	3.9 (-0.1, 9.3)	-6.3 (-9.1, -1.4)
	RCP4.5 in 2050	4/4	-2.5 (-3.7, 0.2)	1.7 (0.6, 2.9)	0.6 (-3.3, 1.9)	-0.1 (-1.7, 6)	-1.2 (-2.6, 2.3)
	↳ 2100		-4.1 (-4.6, 0.7)	4.8 (2, 8)	-1 (-5.5, 1)	-0.2 (-1.4, 9.1)	-3 (-5.2, 2.1)
	Baseline in 2050	4/4	-0.6 (-3.8, 0.4)	0.8 (0, 2.1)	1.5 (-0.7, 3.3)	-1.9 (-3.4, 0.5)	-0.1 (-1.5, 2.9)
	↳ 2100		-0.2 (-2.4, 1.8)	1 (0.2, 2.3)	1 (-2, 2.5)	-2.1 (-3.4, 1.1)	-0.4 (-2.4, 2.8)

** Count of models included / Count of models attempted. One model did not provide land data and is excluded from all entries.*

*** One model could reach RCP1.9 with SSP4, but did not provide land data.*

Figure TS.15 | Pathways linking socioeconomic development, mitigation responses and land (Panel B).

TS

Figure TS.15 (continued): Future scenarios provide a framework for understanding the implications of mitigation and socioeconomics on land. The SSPs span a range of different socioeconomic assumptions (Box SPM.1). They are combined with Representative Concentration Pathways (RCPs)[2] which imply different levels of mitigation. The changes in cropland, pasture, bioenergy cropland, forest, and natural land from 2010 are shown. For this Figure, Cropland includes all land in food, feed, and fodder crops, as well as other arable land (cultivated area). This category includes first generation non-forest bioenergy crops (e.g., corn for ethanol, sugar cane for ethanol, soybeans for biodiesel), but excludes second generation bioenergy crops. Pasture includes categories of pasture land, not only high-quality rangeland, and is based on FAO definition of 'permanent meadows and pastures'. Bioenergy cropland includes land dedicated to second generation energy crops (e.g., switchgrass, miscanthus, fast-growing wood species). Forest includes managed and unmanaged forest. Natural land includes other grassland, savannah, and shrubland. **Panel A:** This panel shows integrated assessment model (IAM)[3] results for SSP1, SSP2 and SSP5 at RCP1.9.[4] For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. For RCP1.9, SSP1, SSP2 and SSP5 results are from five, four and two IAMs respectively. **Panel B**: Land use and land cover change are indicated for various SSP-RCP combinations, showing multi-model median and range (min, max). (Box SPM.1) {1.3.2, 2.7.2, 6.1, 6.4.4, 7.4.2, 7.4.4, 7.4.5, 7.4.6, 7.4.7, 7.4.8, 7.5.3, 7.5.6, Cross-Chapter Box 1 in Chapter 1, Cross-Chapter Box 9 in Chapter 6}

2 Representative Concentration Pathways (RCPs) are scenarios that include timeseries of emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover.

3 Integrated Assessment Models (IAMs) integrate knowledge from two or more domains into a single framework. In this figure, IAMs are used to assess linkages between economic, social and technological development and the evolution of the climate system.

4 The RCP1.9 pathways assessed in this report have a 66% chance of limiting warming to 1.5°C in 2100, but some of these pathways overshoot 1.5°C of warming during the 21st century by >0.1°C.

Summary for Policymakers

SPM

Summary for Policymakers

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Introduction

This Special Report on Climate Change and Land[1] responds to the Panel decision in 2016 to prepare three Special Reports[2] during the Sixth Assessment cycle, taking account of proposals from governments and observer organisations.[3] This report addresses greenhouse gas (GHG) fluxes in land-based ecosystems, land use and sustainable land management[4] in relation to climate change adaptation and mitigation, desertification[5], land degradation[6] and food security[7]. This report follows the publication of other recent reports, including the IPCC *Special Report on Global Warming of 1.5°C* (SR15), the thematic assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on *Land Degradation and Restoration*, the IPBES *Global Assessment Report on Biodiversity and Ecosystem Services*, and the *Global Land Outlook* of the UN Convention to Combat Desertification (UNCCD). This report provides an updated assessment of the current state of knowledge[8] while striving for coherence and complementarity with other recent reports.

This Summary for Policymakers (SPM) is structured in four parts: *A) People, land and climate in a warming world; B) Adaptation and mitigation response options; C) Enabling response options; and, D) Action in the near-term.*

Confidence in key findings is indicated using the IPCC calibrated language; the underlying scientific basis of each key finding is indicated by references to the main report.[9]

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1 The terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation and other biota, and water), the ecological processes, topography, and human settlements and infrastructure that operate within that system.

2 The three Special reports are: *Global Warming of 1.5°C: an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty; Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems; The Ocean and Cryosphere in a Changing Climate.*

3 Related proposals were: climate change and desertification; desertification with regional aspects; land degradation – an assessment of the interlinkages and integrated strategies for mitigation and adaptation; agriculture, forestry and other land use; food and agriculture; and food security and climate change.

4 Sustainable land management is defined in this report as 'the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions'.

5 Desertification is defined in this report as 'land degradation in arid, semi-arid, and dry sub-humid areas resulting from many factors, including climatic variations and human activities'.

6 Land degradation is defined in this report as 'a negative trend in land condition, caused by direct or indirect human induced processes, including anthropogenic climate change, expressed as long-term reduction and as loss of at least one of the following: biological productivity; ecological integrity; or value to humans'.

7 Food security is defined in this report as 'a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life'.

8 The assessment covers literature accepted for publication by 7th April 2019.

9 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, very likely. This is consistent with IPCC AR5.

A. People, land and climate in a warming world

A.1 Land provides the principal basis for human livelihoods and well-being including the supply of food, freshwater and multiple other ecosystem services, as well as biodiversity. Human use directly affects more than 70% (*likely* 69–76%) of the global, ice-free land surface (*high confidence*). Land also plays an important role in the climate system. (Figure SPM.1) {1.1, 1.2, 2.3, 2.4}

A.1.1 People currently use one quarter to one third of land's potential net primary production[10] for food, feed, fibre, timber and energy. Land provides the basis for many other ecosystem functions and services,[11] including cultural and regulating services, that are essential for humanity (*high confidence*). In one economic approach, the world's terrestrial ecosystem services have been valued on an annual basis to be approximately equivalent to the annual global Gross Domestic Product[12] *(medium confidence*). (Figure SPM.1) {1.1, 1.2, 3.2, 4.1, 5.1, 5.5}

A.1.2 Land is both a source and a sink of GHGs and plays a key role in the exchange of energy, water and aerosols between the land surface and atmosphere. Land ecosystems and biodiversity are vulnerable to ongoing climate change, and weather and climate extremes, to different extents. Sustainable land management can contribute to reducing the negative impacts of multiple stressors, including climate change, on ecosystems and societies (*high confidence*). (Figure SPM.1) {1.1, 1.2, 3.2, 4.1, 5.1, 5.5}

A.1.3 Data available since 1961[13] show that global population growth and changes in per capita consumption of food, feed, fibre, timber and energy have caused unprecedented rates of land and freshwater use (*very high confidence*) with agriculture currently accounting for ca. 70% of global fresh-water use (*medium confidence*). Expansion of areas under agriculture and forestry, including commercial production, and enhanced agriculture and forestry productivity have supported consumption and food availability for a growing population (*high confidence*). With large regional variation, these changes have contributed to increasing net GHG emissions (*very high confidence*), loss of natural ecosystems (e.g., forests, savannahs, natural grasslands and wetlands) and declining biodiversity (*high confidence*). (Figure SPM.1) {1.1, 1.3, 5.1, 5.5}

A.1.4 Data available since 1961 shows the per capita supply of vegetable oils and meat has more than doubled and the supply of food calories per capita has increased by about one third (*high confidence*). Currently, 25–30% of total food produced is lost or wasted (*medium confidence*). These factors are associated with additional GHG emissions (*high confidence*). Changes in consumption patterns have contributed to about two billion adults now being overweight or obese (*high confidence*). An estimated 821 million people are still undernourished (*high confidence*). (Figure SPM.1) {1.1, 1.3, 5.1, 5.5}

A.1.5 About a quarter of the Earth's ice-free land area is subject to human-induced degradation (*medium confidence*). Soil erosion from agricultural fields is estimated to be currently 10 to 20 times (no tillage) to more than 100 times (conventional tillage) higher than the soil formation rate (*medium confidence*). Climate change exacerbates land degradation, particularly in low-lying coastal areas, river deltas, drylands and in permafrost areas (*high confidence*). Over the period 1961–2013, the annual area of drylands in drought has increased, on average by slightly more than 1% per year, with large inter-annual variability. In 2015, about 500 (380-620) million people lived within areas which experienced desertification between the 1980s and 2000s. The highest numbers of people affected are in South and East Asia, the circum Sahara region including North Africa, and the Middle East including the Arabian Peninsula (*low confidence*). Other dryland regions have also experienced desertification. People living in already degraded or desertified areas are increasingly negatively affected by climate change (*high confidence*). (Figure SPM.1) {1.1, 1.2, 3.1, 3.2, 4.1, 4.2, 4.3}

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10 Land's potential net primary production (NPP) is defined in this report as 'the amount of carbon accumulated through photosynthesis minus the amount lost by plant respiration over a specified time period that would prevail in the absence of land use'.

11 In its conceptual framework, IPBES uses 'nature's contribution to people' in which it includes ecosystem goods and services.

12 I.e., estimated at $75 trillion for 2011, based on US dollars for 2007.

13 This statement is based on the most comprehensive data from national statistics available within FAOSTAT, which starts in 1961. This does not imply that the changes started in 1961. Land use changes have been taking place from well before the pre-industrial period to the present.

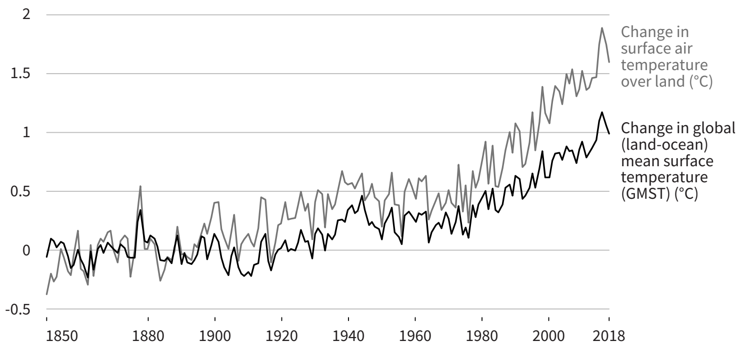
SPM

Land use and observed climate change

A. Observed temperature change relative to 1850-1900

Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST).

CHANGE in TEMPERATURE rel. to 1850-1900 (°C)

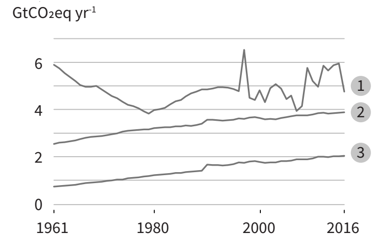


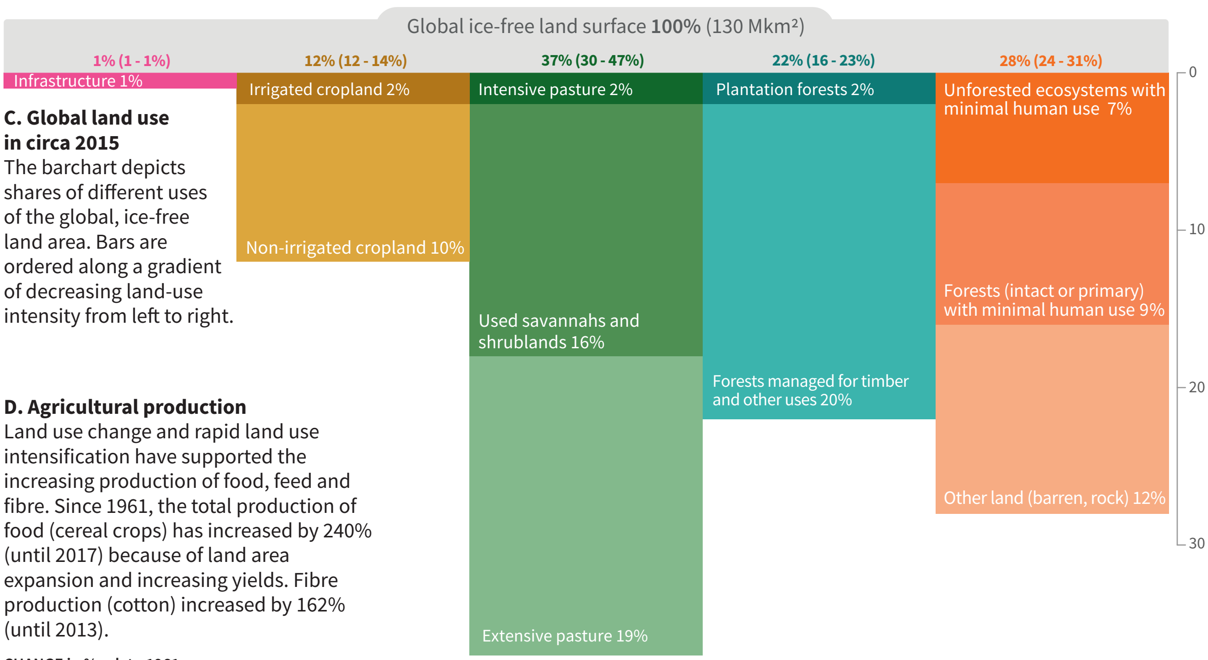
B. GHG emissions

An estimated 23% of total anthropogenic greenhouse gas emissions (2007-2016) derive from Agriculture, Forestry and Other Land Use (AFOLU).

CHANGE in EMISSIONS since 1961

1 Net CO_2 emissions from FOLU ($GtCO_2$ yr^{-1})
2 CH_4 emissions from Agriculture ($GtCO_2eq$ yr^{-1})
3 N_2O emissions from Agriculture ($GtCO_2eq$ yr^{-1})





C. Global land use in circa 2015

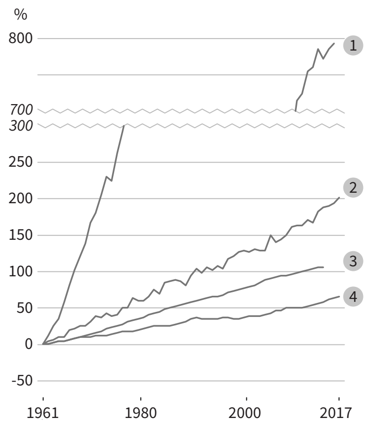
The barchart depicts shares of different uses of the global, ice-free land area. Bars are ordered along a gradient of decreasing land-use intensity from left to right.

D. Agricultural production

Land use change and rapid land use intensification have supported the increasing production of food, feed and fibre. Since 1961, the total production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields. Fibre production (cotton) increased by 162% (until 2013).

CHANGE in % rel. to 1961

1 Inorganic N fertiliser use
2 Cereal yields
3 Irrigation water volume
4 Total number of ruminant livestock

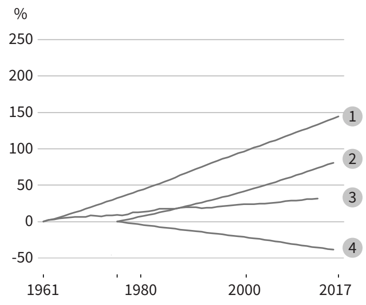


E. Food demand

Increases in production are linked to consumption changes.

CHANGE in % rel. to 1961 and 1975

1 Population
2 Prevalence of overweight + obese
3 Total calories per capita
4 Prevalence of underweight



F. Desertification and land degradation

Land-use change, land-use intensification and climate change have contributed to desertification and land degradation.

CHANGE in % rel. to 1961 and 1970

1 Population in areas experiencing desertification
2 Dryland areas in drought annually
3 Inland wetland extent

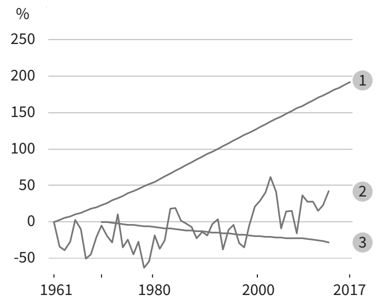


Figure SPM.1: Land use and observed climate change | A representation of the land use and observed climate change covered in this assessment report. Panels A-F show the status and trends in selected land use and climate variables that represent many of the core topics covered in this report. The annual time series in B and D-F are based on the most comprehensive, available data from national statistics, in most cases from FAOSTAT which starts in 1961. Y-axes in panels D-F are expressed relative to the starting year of the time series (rebased to zero). Data sources and notes: **A:** The warming curves are averages of four datasets {2.1, Figure 2.2, Table 2.1} **B:** N_2O and CH_4 from agriculture are from FAOSTAT; Net CO_2 emissions from FOLU using the mean of two bookkeeping models (including emissions from peatland fires since 1997). All values expressed in units of CO_2-eq are based on AR5 100-year Global Warming Potential values without climate-carbon feedbacks (N_2O=265; CH_4=28). (Table SPM.1) {1.1, 2.3} **C:** Depicts shares of different uses of the global, ice-free land area for approximately the year 2015, ordered along a gradient of decreasing land-use intensity from left to right. Each bar represents a broad land cover category; the numbers on top are the total percentage of the ice-free area covered, with uncertainty ranges in brackets. Intensive pasture is defined as having a livestock density greater than 100 animals/km². The area of 'forest managed for timber and other uses' was calculated as total forest area minus 'primary/intact' forest area. {1.2, Table 1.1, Figure 1.3} **D:** Note that fertiliser use is shown on a split axis. The large percentage change in fertiliser use reflects the low level of use in 1961 and relates to both increasing fertiliser input per area as well as the expansion of fertilised cropland and grassland to increase food production. {1.1, Figure 1.3} **E:** Overweight population is defined as having a body mass index (BMI) > 25 kg m^{-2}; underweight is defined as BMI < 18.5 kg m^{-2}. {5.1, 5.2} **F:** Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980-2015) to identify areas where the Aridity Index is below 0.65. Population data are from the HYDE3.2 database. Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index. The inland wetland extent (including peatlands) is based on aggregated data from more than 2000 time series that report changes in local wetland area over time. {3.1, 4.2, 4.6}

A.2 Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature (*high confidence*). Climate change, including increases in frequency and intensity of extremes, has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions (*high confidence*). {2.2, 3.2, 4.2, 4.3, 4.4, 5.1, 5.2, Executive Summary Chapter 7, 7.2}

A.2.1 Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST) (*high confidence*). From 1850-1900 to 2006-2015 mean land surface air temperature has increased by 1.53°C (*very likely* range from 1.38°C to 1.68°C) while GMST increased by 0.87°C (*likely* range from 0.75°C to 0.99°C). (Figure SPM.1) {2.2.1}

A.2.2 Warming has resulted in an increased frequency, intensity and duration of heat-related events, including heatwaves[14] in most land regions (*high confidence*). Frequency and intensity of droughts has increased in some regions (including the Mediterranean, west Asia, many parts of South America, much of Africa, and north-eastern Asia) (*medium confidence*) and there has been an increase in the intensity of heavy precipitation events at a global scale (*medium confidence*). {2.2.5, 4.2.3, 5.2}

A.2.3 Satellite observations[15] have shown vegetation greening[16] over the last three decades in parts of Asia, Europe, South America, central North America, and southeast Australia. Causes of greening include combinations of an extended growing season, nitrogen deposition, Carbon Dioxide (CO_2) fertilisation[17], and land management (*high confidence*). Vegetation browning[18] has been observed in some regions including northern Eurasia, parts of North America, Central Asia and the Congo Basin, largely as a result of water stress (*medium confidence*). Globally, vegetation greening has occurred over a larger area than vegetation browning (*high confidence*). {2.2.3, Box 2.3, 2.2.4, 3.2.1, 3.2.2, 4.3.1, 4.3.2, 4.6.2, 5.2.2}

A.2.4 The frequency and intensity of dust storms have increased over the last few decades due to land use and land cover changes and climate-related factors in many dryland areas resulting in increasing negative impacts on human health, in regions such as the Arabian Peninsula and broader Middle East, Central Asia (*high confidence*).[19] {2.4.1, 3.4.2}

A.2.5 In some dryland areas, increased land surface air temperature and evapotranspiration and decreased precipitation amount, in interaction with climate variability and human activities, have contributed to desertification. These areas include Sub-Saharan Africa, parts of East and Central Asia, and Australia. (*medium confidence*) {2.2, 3.2.2, 4.4.1}

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[14] A heatwave is defined in this report as 'a period of abnormally hot weather'. Heatwaves and warm spells have various and, in some cases, overlapping definitions.

[15] The interpretation of satellite observations can be affected by insufficient ground validation and sensor calibration. In addition their spatial resolution can make it difficult to resolve small-scale changes.

[16] Vegetation greening is defined in this report as 'an increase in photosynthetically active plant biomass which is inferred from satellite observations'.

[17] CO_2 fertilisation is defined in this report as 'the enhancement of plant growth as a result of increased atmospheric carbon dioxide (CO_2) concentration'. The magnitude of CO_2 fertilisation depends on nutrients and water availability.

[18] Vegetation browning is defined in this report as 'a decrease in photosynthetically active plant biomass which is inferred from satellite observations'.

[19] Evidence relative to such trends in dust storms and health impacts in other regions is limited in the literature assessed in this report.

A.2.6 Global warming has led to shifts of climate zones in many world regions, including expansion of arid climate zones and contraction of polar climate zones (*high confidence*). As a consequence, many plant and animal species have experienced changes in their ranges, abundances, and shifts in their seasonal activities (*high confidence*). {2.2, 3.2.2, 4.4.1}

A.2.7 Climate change can exacerbate land degradation processes (*high confidence*) including through increases in rainfall intensity, flooding, drought frequency and severity, heat stress, dry spells, wind, sea-level rise and wave action, and permafrost thaw with outcomes being modulated by land management. Ongoing coastal erosion is intensifying and impinging on more regions with sea-level rise adding to land use pressure in some regions (*medium confidence*). {4.2.1, 4.2.2, 4.2.3, 4.4.1, 4.4.2, 4.9.6, Table 4.1, 7.2.1, 7.2.2}

A.2.8 Climate change has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events (*high confidence*). Studies that separate out climate change from other factors affecting crop yields have shown that yields of some crops (e.g., maize and wheat) in many lower-latitude regions have been affected negatively by observed climate changes, while in many higher-latitude regions, yields of some crops (e.g., maize, wheat, and sugar beets) have been affected positively over recent decades (*high confidence*). Climate change has resulted in lower animal growth rates and productivity in pastoral systems in Africa (*high confidence*). There is robust evidence that agricultural pests and diseases have already responded to climate change resulting in both increases and decreases of infestations (*high confidence*). 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.[20] {5.2.1, 5.2.2, 7.2.2}

A.3 Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2, 44% of methane (CH_4), and 81% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, representing 23% (12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$) of total net anthropogenic emissions of GHGs (*medium confidence*).[21] The natural response of land to human-induced environmental change caused a net sink of around 11.2 $GtCO_2\ yr^{-1}$ during 2007–2016 (equivalent to 29% of total CO2 emissions) (*medium confidence)*; the persistence of the sink is uncertain due to climate change (*high confidence*). If emissions associated with pre- and post-production activities in the global food system[22] are included, the emissions are estimated to be 21–37% of total net anthropogenic GHG emissions (*medium confidence*). {2.3, Table 2.2, 5.4}

A.3.1 Land is simultaneously a source and a sink of CO_2 due to both anthropogenic and natural drivers, making it hard to separate anthropogenic from natural fluxes (*very high confidence*). Global models estimate net CO_2 emissions of 5.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range) from land use and land-use change during 2007–2016. These net emissions are mostly due to deforestation, partly offset by afforestation/reforestation, and emissions and removals by other land use activities (*very high confidence*).[23] There is no clear trend in annual emissions since 1990 (*medium confidence*). (Figure SPM.1, Table SPM.1) {1.1, 2.3, Table 2.2, Table 2.3}

A.3.2 The natural response of land to human-induced environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change, resulted in global net removals of 11.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range) during 2007–2016. The sum of the net removals due to this response and the AFOLU net emissions gives a total net land-atmosphere flux that removed 6.0 ± 3.7 $GtCO_2\ yr^{-1}$ during 2007–2016 (*likely* range). Future net increases in CO_2 emissions from vegetation and soils due to climate change are projected to counteract increased removals due to CO_2 fertilisation and longer growing seasons (*high confidence*). The balance between these processes is a key source of uncertainty for determining the future of the land carbon sink. Projected thawing of permafrost is expected to increase the loss of soil carbon (*high confidence*). During the 21st century, vegetation growth in those areas may compensate in part for this loss (*low confidence*). (Table SPM.1) {Box 2.3, 2.3.1, 2.5.3, 2.7, Table 2.3}

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[20] The assessment covered literature whose methodologies included interviews and surveys with indigenous peoples and local communities.

[21] This assessment only includes CO_2, CH_4 and N_2O.

[22] Global food system in this report is defined as 'all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socioeconomic and environmental outcomes at the global level'. These emissions data are not directly comparable to the national inventories prepared according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

[23] The net anthropogenic flux of CO_2 from 'bookkeeping' or 'carbon accounting' models is composed of two opposing gross fluxes: gross emissions (about 20 $GtCO_2\ yr^{-1}$) are from deforestation, cultivation of soils, and oxidation of wood products; gross removals (about 14 $GtCO_2\ yr^{-1}$) are largely from forest growth following wood harvest and agricultural abandonment (*medium confidence*).

A.3.3 Global models and national GHG inventories use different methods to estimate anthropogenic CO_2 emissions and removals for the land sector. Both produce estimates that are in close agreement for land-use change involving forest (e.g., deforestation, afforestation), and differ for managed forest. Global models consider as managed forest those lands that were subject to harvest whereas, consistent with IPCC guidelines, national GHG inventories define managed forest more broadly. On this larger area, inventories can also consider the natural response of land to human-induced environmental changes as anthropogenic, while the global model approach (Table SPM.1) treats this response as part of the non-anthropogenic sink. For illustration, from 2005 to 2014, the sum of the national GHG inventories net emission estimates is 0.1 ± 1.0 $GtCO_2\ yr^{-1}$, while the mean of two global bookkeeping models is 5.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range). Consideration of differences in methods can enhance understanding of land sector net emission estimates and their applications. {2.4.1, 2.7.3, Fig 2.5, Box 2.2}

Net anthropogenic emissions due to Agriculture, Forestry, and other Land Use (AFOLU) and non-AFOLU (Panel 1) and global food systems (average for 2007–2016)[1] (Panel 2). Positive values represent emissions; negative values represent removals.

		Direct Anthropogenic							
Gas	Units	Net anthropogenic emissions due to Agriculture, Forestry, and Other Land Use (AFOLU)			Non-AFOLU anthropogenic GHG emissions[6]	Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions, by gas	Natural response of land to human-induced environmental change[7]	Net land – atmosphere flux from all lands
Panel 1: Contribution of AFOLU									
		FOLU	Agriculture	Total					
		A	B	C = A + B	D	**E = C + D**	F = (C/E) ×100	G	A + G
CO_2[2]	$GtCO_2\ yr^{-1}$	5.2 ± 2.6	No data[11]	5.2 ± 2.6	33.9 ± 1.8	**39.1 ± 3.2**	13%	-11.2 ± 2.6	-6.0 ± 3.7
CH_4[3,8]	$MtCH_4\ yr^{-1}$	19.2 ± 5.8	142 ± 42	161 ± 43	201 ± 101	**362 ± 109**			
	$GtCO_2eq\ yr^{-1}$	0.5 ± 0.2	4.0 ± 1.2	4.5 ± 1.2	5.6 ± 2.8	**10.1 ± 3.1**	44%		
N_2O[3,8]	$MtN_2O\ yr^{-1}$	0.3 ± 0.1	8.3 ± 2.5	8.7 ± 2.5	2.0 ± 1.0	**10.6 ± 2.7**			
	$GtCO_2eq\ yr^{-1}$	0.09 ± 0.03	2.2 ± 0.7	2.3 ± 0.7	0.5 ± 0.3	**2.8 ± 0.7**	81%		
Total (GHG)	**$GtCO_2eq\ yr^{-1}$**	**5.8 ± 2.6**	**6.2 ± 1.4**	**12.0 ± 2.9**	**40.0 ± 3.4**	**52.0 ± 4.5**	**23%**		
Panel 2: Contribution of global food system									
		Land-use change	Agriculture		Non-AFOLU[5] other sectors pre- to post-production	Total global food system emissions			
CO_2 Land-use change[4]	$GtCO_2\ yr^{-1}$	4.9 ± 2.5							
CH_4 Agriculture[3,8,9]	$GtCO_2eq\ yr^{-1}$		4.0 ± 1.2						
N_2O Agriculture[3,8,9]	$GtCO_2eq\ yr^{-1}$		2.2 ± 0.7						
CO_2 other sectors[5]	$GtCO_2 yr^{-1}$				2.6 – 5.2				
Total[10]	**$GtCO_2eq\ yr^{-1}$**	**4.9 ± 2.5**	**6.2 ± 1.4**		**2.6 – 5.2**	**10.8 – 19.1**			

Table SPM.1 | Data sources and notes:

[1] Estimates are only given until 2016 as this is the latest date when data are available for all gases.

[2] Net anthropogenic flux of CO_2 due to land cover change such as deforestation and afforestation, and land management including wood harvest and regrowth, as well as peatland burning, based on two bookkeeping models as used in the Global Carbon Budget and for AR5. Agricultural soil carbon stock change under the same land use is not considered in these models. {2.3.1.2.1, Table 2.2, Box 2.2}

[3] Estimates show the mean and assessed uncertainty of two databases, FAOSTAT and USEPA. 2012 {2.3, Table 2.2}

[4] Based on FAOSTAT. Categories included in this value are 'net forest conversion' (net deforestation), drainage of organic soils (cropland and grassland), biomass burning (humid tropical forests, other forests, organic soils). It excludes 'forest land' (forest management plus net forest expansion), which is primarily a sink due to afforestation. Note: Total FOLU emissions from FAOSTAT are 2.8 (±1.4) $GtCO_2\ yr^{-1}$ for the period 2007–2016. {Table 2.2, Table 5.4}

[5] CO_2 emissions induced by activities not included in the AFOLU sector, mainly from energy (e.g., grain drying), transport (e.g., international trade), and industry (e.g., synthesis of inorganic fertilisers) part of food systems, including agricultural production activities (e.g., heating in greenhouses), pre-production (e.g., manufacturing of farm inputs) and post-production (e.g., agri-food processing) activities. This estimate is land based and hence excludes emissions from fisheries. It includes emissions from fibre and other non-food agricultural products since these are not separated from food use in databases. The CO_2 emissions related to the food system in sectors other than AFOLU are 6–-13% of total anthropogenic CO_2 emissions. These emissions are typically low in smallholder subsistence farming. When added to AFOLU emissions, the estimated share of food systems in global anthropogenic emissions is 21–-37%. {5.4.5, Table 5.4}

[6] Total non-AFOLU emissions were calculated as the sum of total CO_2eq emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping and from the PRIMAP database for CH_4 and N_2O averaged over 2007–2014 only as that was the period for which data were available. {2.3, Table 2.2}.

[7] The natural response of land to human-induced environmental changes is the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change. The estimate shown represents the average from Dynamic Global Vegetation Models {2.3.1.2, Box 2.2, Table 2.3}

[8] All values expressed in units of CO_2eq are based on AR5 100-year Global Warming Potential (GWP) values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28). Note that the GWP has been used across fossil fuel and biogenic sources of methane. If a higher GWP for fossil fuel CH_4 (30 per AR5) were used, then total anthropogenic CH_4 emissions expressed in CO_2eq would be 2% greater.

[9] This estimate is land based and hence excludes emissions from fisheries and emissions from aquaculture (except emissions from feed produced on land and used in aquaculture), and also includes non-food use (e.g. fibre and bioenergy) since these are not separated from food use in databases. It excludes non-CO_2 emissions associated with land use change (FOLU category) since these are from fires in forests and peatlands.

[10] Emissions associated with food loss and waste are included implicitly, since emissions from the food system are related to food produced, including food consumed for nutrition and to food loss and waste. The latter is estimated at 8–10% of total anthropogenic emissions in CO_2eq. {5.5.2.5}

[11] No global data are available for agricultural CO_2 emissions.

A.3.4 Global AFOLU emissions of methane in the period 2007–2016 were 161 ± 43 $MtCH_4\ yr^{-1}$ (4.5 ± 1.2 $GtCO_2eq\ yr^{-1}$) (*medium confidence*). The globally averaged atmospheric concentration of CH_4 shows a steady increase between the mid-1980s and early 1990s, slower growth thereafter until 1999, a period of no growth between 1999–2006, followed by a resumption of growth in 2007 (*high confidence*). Biogenic sources make up a larger proportion of emissions than they did before 2000 (*high confidence*). Ruminants and the expansion of rice cultivation are important contributors to the rising concentration (*high confidence*). (Figure SPM.1) {Table 2.2, 2.3.2, 5.4.2, 5.4.3}

A.3.5 Anthropogenic AFOLU N_2O emissions are rising, and were 8.7 ± 2.5 $MtN_2O\ yr^{-1}$ (2.3 ± 0.7 $GtCO_2eq\ yr^{-1}$) during the period 2007-2016. Anthropogenic N_2O emissions {Figure SPM.1, Table SPM.1} from soils are primarily due to nitrogen application including inefficiencies (over-application or poorly synchronised with crop demand timings) (*high confidence*). Cropland soils emitted around 3 $MtN_2O\ yr^{-1}$ (around 795 $MtCO_2\ eq\ yr^{-1}$) during the period 2007–2016 (*medium confidence*). There has been a major growth in emissions from managed pastures due to increased manure deposition (*medium confidence*). Livestock on managed pastures and rangelands accounted for more than one half of total anthropogenic N_2O emissions from agriculture in 2014 (*medium confidence*). {Table 2.1, 2.3.3, 5.4.2, 5.4.3}

A.3.6 Total net GHG emissions from AFOLU emissions represent 12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$ during 2007–2016. This represents 23% of total net anthropogenic emissions {Table SPM.1}.[24] Other approaches, such as global food system, include agricultural emissions and land use change (i.e., deforestation and peatland degradation), as well as outside farm gate emissions from energy, transport and industry sectors for food production. Emissions within farm gate and from agricultural land expansion contributing to the global food system represent 16–27% of total anthropogenic emissions (*medium confidence*). Emissions outside the farm gate represent 5–10% of total anthropogenic emissions (*medium confidence*). Given the diversity of food systems, there are large regional differences in the contributions from different components of the food system (*very high confidence*). Emissions from agricultural production are projected to increase (*high confidence*), driven by population and income growth and changes in consumption patterns (*medium confidence*). {5.5, Table 5.4}

[24] This assessment only includes CO_2, CH_4 and N_2O.

A.4 Changes in land conditions,[25] either from land-use or climate change, affect global and regional climate (*high confidence*). At the regional scale, changing land conditions can reduce or accentuate warming and affect the intensity, frequency and duration of extreme events. The magnitude and direction of these changes vary with location and season (*high confidence*). {Executive Summary Chapter 2, 2.3, 2.4, 2.5, 3.3}

A.4.1 Since the pre-industrial period, changes in land cover due to human activities have led to both a net release of CO_2 contributing to global warming (*high confidence*), and an increase in global land albedo[26] causing surface cooling (*medium confidence*). Over the historical period, the resulting net effect on globally averaged surface temperature is estimated to be small (*medium confidence*). {2.4, 2.6.1, 2.6.2}

A.4.2 The likelihood, intensity and duration of many extreme events can be significantly modified by changes in land conditions, including heat related events such as heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*). Changes in land conditions can affect temperature and rainfall in regions as far as hundreds of kilometres away (*high confidence*). {2.5.1, 2.5.2, 2.5.4, 3.3, Cross-Chapter Box 4 in Chapter 2}

A.4.3 Climate change is projected to alter land conditions with feedbacks on regional climate. In those boreal regions where the treeline migrates northward and/or the growing season lengthens, winter warming will be enhanced due to decreased snow cover and albedo while warming will be reduced during the growing season because of increased evapotranspiration (*high confidence*). In those tropical areas where increased rainfall is projected, increased vegetation growth will reduce regional warming (*medium confidence*). Drier soil conditions resulting from climate change can increase the severity of heat waves, while wetter soil conditions have the opposite effect (*high confidence*). {2.5.2, 2.5.3}

A.4.4 Desertification amplifies global warming through the release of CO_2 linked with the decrease in vegetation cover (*high confidence*). This decrease in vegetation cover tends to increase local albedo, leading to surface cooling (*high confidence*). {3.3}

A.4.5 Changes in forest cover, for example from afforestation, reforestation and deforestation, directly affect regional surface temperature through exchanges of water and energy (*high confidence*).[27] Where forest cover increases in tropical regions cooling results from enhanced evapotranspiration (*high confidence*). Increased evapotranspiration can result in cooler days during the growing season (*high confidence*) and can reduce the amplitude of heat related events (*medium confidence*). In regions with seasonal snow cover, such as boreal and some temperate regions, increased tree and shrub cover also has a wintertime warming influence due to reduced surface albedo (*high confidence*).[28] {2.3, 2.4.3, 2.5.1, 2.5.2, 2.5.4}

A.4.6 Both global warming and urbanisation can enhance warming in cities and their surroundings (heat island effect), especially during heat related events, including heat waves (*high confidence*). Night-time temperatures are more affected by this effect than daytime temperatures (*high confidence*). Increased urbanisation can also intensify extreme rainfall events over the city or downwind of urban areas (*medium confidence*). {2.5.1, 2.5.2, 2.5.3, 4.9.1, Cross-Chapter Box 4 in Chapter 2}

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[25] Land conditions encompass changes in land cover (e.g., deforestation, afforestation, urbanisation), in land use (e.g., irrigation), and in land state (e.g., degree of wetness, degree of greening, amount of snow, amount of permafrost).

[26] Land with high albedo reflects more incoming solar radiation than land with low albedo.

[27] The literature indicates that forest cover changes can also affect climate through changes in emissions of reactive gases and aerosols. {2.4, 2.5}

[28] Emerging literature shows that boreal forest-related aerosols may counteract at least partly the warming effect of surface albedo. {2.4.3}

Box SPM. 1 | Shared Socio-economic Pathways (SSPs)

In this report the implications of future socio-economic development on climate change mitigation, adaptation and land-use are explored using shared socio-economic pathways (SSPs). The SSPs span a range of challenges to climate change mitigation and adaptation.

- SSP1 includes a peak and decline in population (~7 billion in 2100), high income and reduced inequalities, effective land-use regulation, less resource intensive consumption, including food produced in low-GHG emission systems and lower food waste, free trade and environmentally-friendly technologies and lifestyles. Relative to other pathways, SSP1 has low challenges to mitigation and low challenges to adaptation (i.e., high adaptive capacity)

- SSP2 includes medium population growth (~9 billion in 2100), medium income, technological progress, production and consumption patterns are a continuation of past trends, and only a gradual reduction in inequality occurs. Relative to other pathways, SSP2 has medium challenges to mitigation and medium challenges to adaptation (i.e., medium adaptive capacity).

- SSP3 includes high population growth (~13 billion in 2100), low income and continued inequalities, material-intensive consumption and production, barriers to trade, and slow rates of technological change. Relative to other pathways, SSP3 has high challenges to mitigation and high challenges to adaptation (i.e., low adaptive capacity).

- SSP4 includes medium population growth (~9 billion in 2100), medium income, but significant inequality within and across regions. Relative to other pathways, SSP4 has low challenges to mitigation, but high challenges to adaptation (i.e., low adaptive capacity).

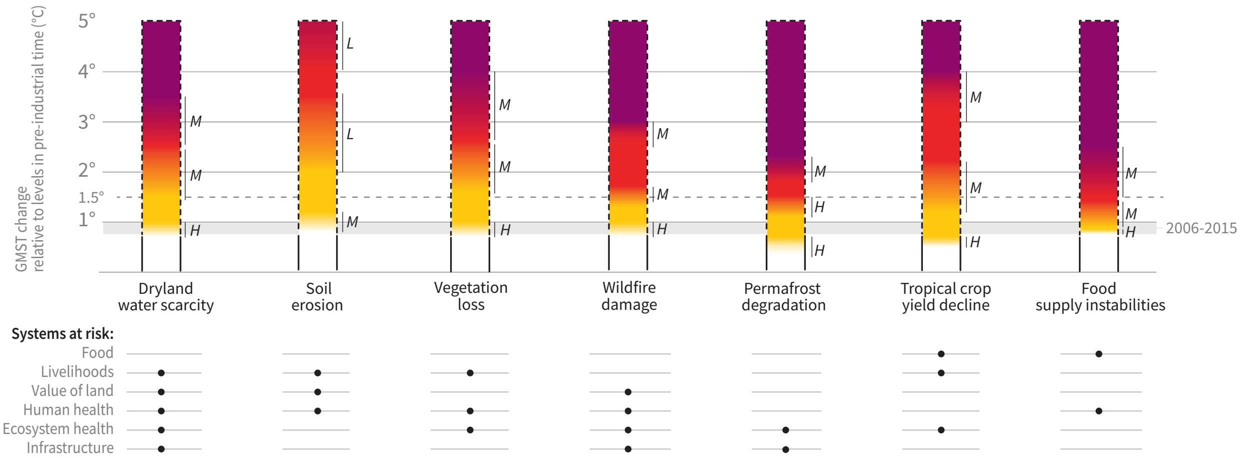
- SSP5 includes a peak and decline in population (~7 billion in 2100), high income, reduced inequalities, and free trade. This pathway includes resource-intensive production, consumption and lifestyles. Relative to other pathways, SSP5 has high challenges to mitigation, but low challenges to adaptation (i.e., high adaptive capacity).

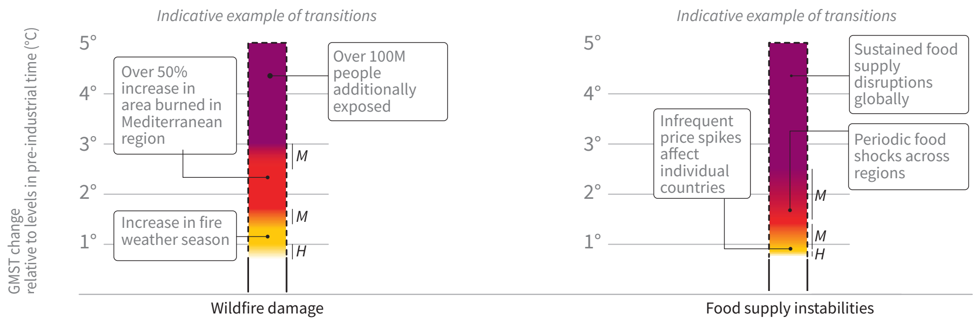
- The SSPs can be combined with Representative Concentration Pathways (RCPs) which imply different levels of mitigation, with implications for adaptation. Therefore, SSPs can be consistent with different levels of global mean surface temperature rise as projected by different SSP-RCP combinations. However, some SSP-RCP combinations are not possible; for instance RCP2.6 and lower levels of future global mean surface temperature rise (e.g., 1.5ºC) are not possible in SSP3 in modelled pathways. {1.2.2, 6.1.4, Cross-Chapter Box 1 in Chapter 1, Cross-Chapter Box 9 in Chapter 6}

SPM

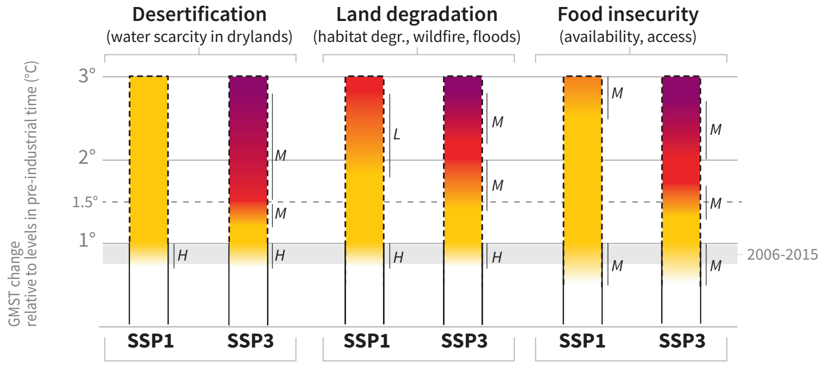
A. Risks to humans and ecosystems from changes in land-based processes as a result of climate change

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





B. Different socioeconomic pathways affect levels of climate related risks



Socio-economic choices can reduce or exacerbate climate related risks as well as influence the rate of temperature increase. The **SSP1** pathway illustrates a world with low population growth, high income and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity. The **SSP3** pathway has the opposite trends. Risks are lower in SSP1 compared with SSP3 given the same level of GMST increase.

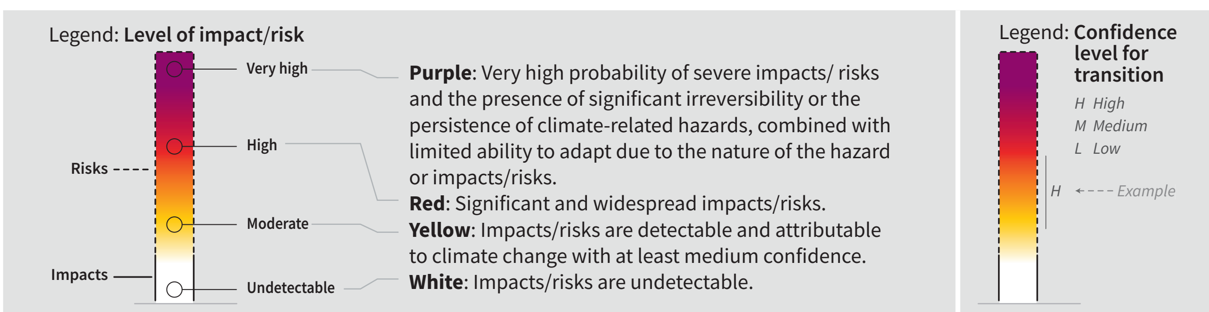


Figure SPM.2: Risks to land-related human systems and ecosystems from global climate change, socio-economic development and mitigation choices in terrestrial ecosystems. | As in previous IPCC reports the literature was used to make expert judgements to assess the levels of global warming at which levels of risk are undetectable, moderate, high or very high, as described further in Chapter 7 and other parts of the underlying report. The Figure indicates assessed risks at approximate warming levels which may be influenced by a variety of factors, including adaptation responses. The assessment considers adaptive capacity consistent with the SSP pathways as described below. **Panel A**: Risks to selected elements of the land system as a function of global mean surface temperature {2.1, Box 2.1, 3.5, 3.7.1.1, 4.4.1.1, 4.4.1.2, 4.4.1.3, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 7.2, 7.3, Table SM7.1}. Links to broader systems are illustrative and not intended to be comprehensive. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway. {Table SM7.4} **Panel B**: Risks associated with desertification, land degradation and food security due to climate change and patterns of socio-economic development. Increasing risks associated with desertification include population exposed and vulnerable to water scarcity in drylands. Risks related to land degradation include increased habitat degradation, population exposed to wildfire and floods and costs of floods. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable due to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3 {Box SPM.1}) excluding the effects of targeted mitigation policies. {3.5, 4.2.1.2, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 6.1.4, 7.2, Table SM7.5} Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change. **All panels:** As part of the assessment, literature was compiled and data extracted into a summary table. A formal expert elicitation protocol (based on modified-Delphi technique and the Sheffield Elicitation Framework), was followed to identify risk transition thresholds. This included a multi-round elicitation process with two rounds of independent anonymous threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 7 Supplementary Material.

A.5 Climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (*high confidence*). Increasing impacts on land are projected under all future GHG emission scenarios (*high confidence*). Some regions will face higher risks, while some regions will face risks previously not anticipated (*high confidence*). Cascading risks with impacts on multiple systems and sectors also vary across regions (*high confidence*). (Figure SPM.2) {2.2, 3.5, 4.2, 4.4, 4.7, 5.1, 5.2, 5.8, 6.1, 7.2, 7.3, Cross-Chapter Box 9 in Chapter 6}

A.5.1 With increasing warming, the frequency, intensity and duration of heat related events including heatwaves are projected to continue to increase through the 21st century (*high confidence*). The frequency and intensity of droughts are projected to increase particularly in the Mediterranean region and southern Africa (*medium confidence*). The frequency and intensity of extreme rainfall events are projected to increase in many regions (*high confidence*). {2.2.5, 3.5.1, 4.2.3, 5.2}

A.5.2 With increasing warming, climate zones are projected to further shift poleward in the middle and high latitudes (*high confidence*). In high-latitude regions, warming is projected to increase disturbance in boreal forests, including drought, wildfire, and pest outbreaks (*high confidence*). In tropical regions, under medium and high GHG emissions scenarios, warming is projected to result in the emergence of unprecedented[29] climatic conditions by the mid to late 21st century (*medium confidence*). {2.2.4, 2.2.5, 2.5.3, 4.3.2}

A.5.3 Current levels of global warming are associated with moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation and tropical crop yield decline (*high confidence*). Risks, including cascading risks, are projected to become increasingly severe with increasing temperatures. At around 1.5°C of global warming the risks from dryland water scarcity, wildfire damage, permafrost degradation and food supply instabilities are projected to be high (*medium confidence*). At around 2°C of global warming the risk from permafrost degradation and food supply instabilities are projected to be very high (*medium confidence*). Additionally, at around 3°C of global warming risk from vegetation loss, wildfire damage, and dryland water scarcity are also projected to be very high (*medium confidence*). Risks from droughts, water stress, heat related events such as heatwaves and habitat degradation simultaneously increase between 1.5°C and 3°C warming (*low confidence*). (Figure SPM.2) {7.2.2, Cross-Chapter Box 9 in Chapter 6, Chapter 7 Supplementary Material}

A.5.4 The stability of food supply[30] is projected to decrease as the magnitude and frequency of extreme weather events that disrupt food chains increases (*high confidence*). Increased atmospheric CO_2 levels can also lower the nutritional quality of crops (*high confidence*). In SSP2, global crop and economic models project a median increase of 7.6% (range of 1–23%) in cereal prices in 2050 due to climate change (RCP6.0), leading to higher food prices and increased risk of food insecurity and hunger (*medium*

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29 Unprecedented climatic conditions are defined in this report as 'not having occurred anywhere during the 20th century'. They are characterised by high temperature with strong seasonality and shifts in precipitation. In the literature assessed, the effect of climatic variables other than temperature and precipitation were not considered.

30 The supply of food is defined in this report as 'encompassing availability and access (including price)'. Food supply instability refers to variability that influences food security through reducing access.

confidence). The most vulnerable people will be more severely affected (*high confidence*). {5.2.3, 5.2.4, 5.2.5, 5.8.1, 7.2.2.2, 7.3.1}

A.5.5 In drylands, climate change and desertification are projected to cause reductions in crop and livestock productivity (*high confidence*), modify the plant species mix and reduce biodiversity (*medium confidence*). Under SSP2, the dryland population vulnerable to water stress, drought intensity and habitat degradation is projected to reach 178 million people by 2050 at 1.5°C warming, increasing to 220 million people at 2°C warming, and 277 million people at 3°C warming (*low confidence*). {3.5.1, 3.5.2, 3.7.3}

A.5.6 Asia and Africa[31] are projected to have the highest number of people vulnerable to increased desertification. North America, South America, Mediterranean, southern Africa and central Asia may be increasingly affected by wildfire. The tropics and subtropics are projected to be most vulnerable to crop yield decline. Land degradation resulting from the combination of sea-level rise and more intense cyclones is projected to jeopardise lives and livelihoods in cyclone prone areas (*very high confidence*). Within populations, women, the young, elderly and poor are most at risk (*high confidence*). {3.5.1, 3.5.2, 4.4, Table 4.1, 5.2.2, 7.2.2, Cross-Chapter Box 3 in Chapter 2}

A.5.7 Changes in climate can amplify environmentally induced migration both within countries and across borders (*medium confidence*), reflecting multiple drivers of mobility and available adaptation measures (*high confidence*). Extreme weather and climate or slow-onset events may lead to increased displacement, disrupted food chains, threatened livelihoods (*high confidence*), and contribute to exacerbated stresses for conflict (*medium confidence*). {3.4.2, 4.7.3, 5.2.3, 5.2.4, 5.2.5, 5.8.2, 7.2.2, 7.3.1}

A.5.8 Unsustainable land management has led to negative economic impacts (*high confidence*). Climate change is projected to exacerbate these negative economic impacts (*high confidence*). {4.3.1, 4.4.1, 4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8, 5.2, 5.8.1, 7.3.4, 7.6.1, Cross-Chapter Box 10 in Chapter 7}

A.6 The level of risk posed by climate change depends both on the level of warming and on how population, consumption, production, technological development, and land management patterns evolve (*high confidence*). Pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture yields result in higher risks from water scarcity in drylands, land degradation, and food insecurity (*high confidence*). (Figure SPM.2b) {5.1.4, 5.2.3, 6.1.4, 7.2, Cross-Chapter Box 9 in Chapter 6}

A.6.1 Projected increases in population and income, combined with changes in consumption patterns, result in increased demand for food, feed, and water in 2050 in all SSPs (*high confidence*). These changes, combined with land management practices, have implications for land-use change, food insecurity, water scarcity, terrestrial GHG emissions, carbon sequestration potential, and biodiversity (*high confidence*). Development pathways in which incomes increase and the demand for land conversion is reduced, either through reduced agricultural demand or improved productivity, can lead to reductions in food insecurity (*high confidence*). All assessed future socio-economic pathways result in increases in water demand and water scarcity (*high confidence*). SSPs with greater cropland expansion result in larger declines in biodiversity (*high confidence*). {6.1.4}

A.6.2 Risks related to water scarcity in drylands are lower in pathways with low population growth, less increase in water demand, and high adaptive capacity, as in SSP1. In these scenarios the risk from water scarcity in drylands is moderate even at global warming of 3°C (*low confidence*). By contrast, risks related to water scarcity in drylands are greater for pathways with high population growth, high vulnerability, higher water demand, and low adaptive capacity, such as SSP3. In SSP3 the transition from moderate to high risk occurs between 1.2°C and 1.5°C (*medium confidence*). (Figure SPM.2b, Box SPM.1) {7.2}

A.6.3 Risks related to climate change driven land degradation are higher in pathways with a higher population, increased land-use change, low adaptive capacity and other barriers to adaptation (e.g., SSP3). These scenarios result in more people exposed to ecosystem degradation, fire, and coastal flooding (*medium confidence*). For land degradation, the projected transition from moderate to high risk occurs for global warming between 1.8°C and 2.8°C in SSP1 (*low confidence*) and between 1.4°C and 2°C in SSP3 (*medium confidence*). The projected transition from high to very high risk occurs between 2.2°C and 2.8°C for SSP3 (*medium confidence*). (Figure SPM.2b) {4.4, 7.2}

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31 West Africa has a high number of people vulnerable to increased desertification and yield decline. North Africa is vulnerable to water scarcity.

A.6.4 Risks related to food security are greater in pathways with lower income, increased food demand, increased food prices resulting from competition for land, more limited trade, and other challenges to adaptation (e.g., SSP3) (*high confidence*). For food security, the transition from moderate to high risk occurs for global warming between 2.5°C and 3.5°C in SSP1 (*medium confidence*) and between 1.3°C and 1.7°C in SSP3 (*medium confidence*). The transition from high to very high risk occurs between 2°C and 2.7°C for SSP3 (*medium confidence*). (Figure SPM.2b) {7.2}

A.6.5 Urban expansion is projected to lead to conversion of cropland leading to losses in food production (*high confidence*). This can result in additional risks to the food system. Strategies for reducing these impacts can include urban and peri-urban food production and management of urban expansion, as well as urban green infrastructure that can reduce climate risks in cities[32] (*high confidence*). (Figure SPM.3) {4.9.1, 5.5, 5.6, 6.3, 6.4, 7.5.6}

[32] The land systems considered in this report do not include urban ecosystem dynamics in detail. Urban areas, urban expansion, and other urban processes and their relation to land-related processes are extensive, dynamic, and complex. Several issues addressed in this report such as population, growth, incomes, food production and consumption, food security, and diets have close relationships with these urban processes. Urban areas are also the setting of many processes related to land-use change dynamics, including loss of ecosystem functions and services, that can lead to increased disaster risk. Some specific urban issues are assessed in this report.

SPM

B. Adaptation and mitigation response options

B.1 Many land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security. The potential for land-related responses and the relative emphasis on adaptation and mitigation is context specific, including the adaptive capacities of communities and regions. While land-related response options can make important contributions to adaptation and mitigation, there are some barriers to adaptation and limits to their contribution to global mitigation. (*very high confidence*) (Figure SPM.3) {2.6, 4.8, 5.6, 6.1, 6.3, 6.4}

B.1.1 Some land-related actions are already being taken that contribute to climate change adaptation, mitigation and sustainable development. The response options were assessed across adaptation, mitigation, combating desertification and land degradation, food security and sustainable development, and a select set of options deliver across all of these challenges. These options include, but are not limited to, sustainable food production, improved and sustainable forest management, soil organic carbon management, ecosystem conservation and land restoration, reduced deforestation and degradation, and reduced food loss and waste (*high confidence*). These response options require integration of biophysical, socioeconomic and other enabling factors. {6.3, 6.4.5, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

B.1.2 While some response options have immediate impacts, others take decades to deliver measurable results. Examples of response options with immediate impacts include the conservation of high-carbon ecosystems such as peatlands, wetlands, rangelands, mangroves and forests. Examples that provide multiple ecosystem services and functions, but take more time to deliver, include afforestation and reforestation as well as the restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils (*high confidence*). {6.4.5, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

B.1.3 The successful implementation of response options depends on consideration of local environmental and socio-economic conditions. Some options such as soil carbon management are potentially applicable across a broad range of land use types, whereas the efficacy of land management practices relating to organic soils, peatlands and wetlands, and those linked to freshwater resources, depends on specific agro-ecological conditions (*high confidence*). Given the site-specific nature of climate change impacts on food system components and wide variations in agroecosystems, adaptation and mitigation options and their barriers are linked to environmental and cultural context at regional and local levels (*high confidence*). Achieving land degradation neutrality depends on the integration of multiple responses across local, regional and national scales and across multiple sectors including agriculture, pasture, forest and water (*high confidence*). {4.8, 6.2, 6.3, 6.4.4, 7.5.6}

B.1.4 Land-based options that deliver carbon sequestration in soil or vegetation, such as afforestation, reforestation, agroforestry, soil carbon management on mineral soils, or carbon storage in harvested wood products, do not continue to sequester carbon indefinitely (*high confidence*). Peatlands, however, can continue to sequester carbon for centuries (*high confidence*). When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero, while carbon stocks can be maintained (*high confidence*). However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management (*high confidence*). {6.4.1}

B.2 Most of the response options assessed contribute positively to sustainable development and other societal goals (*high confidence*). Many response options can be applied without competing for land and have the potential to provide multiple co-benefits (*high confidence*). A further set of response options has the potential to reduce demand for land, thereby enhancing the potential for other response options to deliver across each of climate change adaptation and mitigation, combating desertification and land degradation, and enhancing food security (*high confidence*). (Figure SPM.3) {4.8, 6.2, 6.3.6, 6.4.3}

B.2.1 A number of land management options, such as improved management of cropland and grazing lands, improved and sustainable forest management, and increased soil organic carbon content, do not require land use change and do not create demand for more land conversion (*high confidence*). Further, a number of response options such as increased food productivity, dietary choices and food losses, and waste reduction, can reduce demand for land conversion, thereby potentially freeing land and creating opportunities for enhanced implementation of other response options (*high confidence*). Response options that reduce competition for land are possible and are applicable at different scales, from farm to regional (*high confidence*). (Figure SPM.3) {4.8, 6.3.6, 6.4}

B.2.2 A wide range of adaptation and mitigation responses, e.g., preserving and restoring natural ecosystems such as peatland, coastal lands and forests, biodiversity conservation, reducing competition for land, fire management, soil management, and most risk management options (e.g., use of local seeds, disaster risk management, risk sharing instruments) have the potential to make positive contributions to sustainable development, enhancement of ecosystem functions and services and other societal goals (*medium confidence*). Ecosystem-based adaptation can, in some contexts, promote nature conservation while alleviating poverty and can even provide co-benefits by removing GHGs and protecting livelihoods (e.g., mangroves) (*medium confidence*). {6.4.3, 7.4.6.2}

B.2.3 Most of the land management-based response options that do not increase competition for land, and almost all options based on value chain management (e.g., dietary choices, reduced post-harvest losses, reduced food waste) and risk management, can contribute to eradicating poverty and eliminating hunger while promoting good health and wellbeing, clean water and sanitation, climate action, and life on land (*medium confidence*). {6.4.3}

B.3 Although most response options can be applied without competing for available land, some can increase demand for land conversion (*high confidence*). At the deployment scale of several $GtCO_2$ yr^{-1}, this increased demand for land conversion could lead to adverse side effects for adaptation, desertification, land degradation and food security (*high confidence*). If applied on a limited share of total land and integrated into sustainably managed landscapes, there will be fewer adverse side-effects and some positive co-benefits can be realised (*high confidence*). (Figure SPM.3) {4.5, 6.2, 6.4, Cross-Chapter Box 7 in Chapter 6}

B.3.1 If applied at scales necessary to remove CO_2 from the atmosphere at the level of several $GtCO_2$ yr^{-1}, afforestation, reforestation and the use of land to provide feedstock for bioenergy with or without carbon capture and storage, or for biochar, could greatly increase demand for land conversion (*high confidence*). Integration into sustainably managed landscapes at appropriate scale can ameliorate adverse impacts (*medium confidence*). Reduced grassland conversion to croplands, restoration and reduced conversion of peatlands, and restoration and reduced conversion of coastal wetlands affect smaller land areas globally, and the impacts on land use change of these options are smaller or more variable (*high confidence*). (Figure SPM.3) {Cross-Chapter Box 7 in Chapter 6, 6.4}

B.3.2 While land can make a valuable contribution to climate change mitigation, there are limits to the deployment of land-based mitigation measures such as bioenergy crops or afforestation. Widespread use at the scale of several millions of km^2 globally could increase risks for desertification, land degradation, food security and sustainable development (*medium confidence*). Applied on a limited share of total land, land-based mitigation measures that displace other land uses have fewer adverse side-effects and can have positive co-benefits for adaptation, desertification, land degradation or food security. (*high confidence*) (Figure SPM.3) {4.2, 4.5, 6.4; Cross-Chapter Box 7 in Chapter 6}

B.3.3 The production and use of biomass for bioenergy can have co-benefits, adverse side-effects, and risks for land degradation, food insecurity, GHG emissions and other environmental and sustainable development goals (*high confidence*). These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime, and other land-demanding response options can have a similar range of consequences (*high confidence*). The use of residues and organic waste as bioenergy feedstock can mitigate land use change pressures associated with bioenergy deployment, but residues are limited and the removal of residues that would otherwise be left on the soil could lead to soil degradation (*high confidence*). (Figure SPM.3) {2.6.1.5, Cross-Chapter Box 7 in Chapter 6}

B.3.4 For projected socioeconomic pathways with low population, effective land-use regulation, food produced in low-GHG emission systems and lower food loss and waste (SSP1), the transition from low to moderate risk to food security, land degradation and water scarcity in dry lands occur between 1 and 4 million km^2 of bioenergy or bioenergy with carbon capture and storage (BECCS) (*medium confidence*). By contrast, in pathways with high population, low income and slow rates of technological change (SSP3), the transition from low to moderate risk occurs between 0.1 and 1 million km^2 (*medium confidence*). (Box SPM.1) {6.4, Table SM7.6, Cross-Chapter Box 7 in Chapter 6}

B.4 Many activities for combating desertification can contribute to climate change adaptation with mitigation co-benefits, as well as to halting biodiversity loss with sustainable development co-benefits to society (*high confidence*). Avoiding, reducing and reversing desertification would enhance soil fertility, increase carbon storage in soils and biomass, while benefitting agricultural productivity and food security (*high confidence*). Preventing desertification is preferable to attempting to restore degraded land due to the potential for residual risks and maladaptive outcomes (*high confidence*). {3.6.1, 3.6.2, 3.6.3, 3.6.4, 3.7.1, 3.7.2}

B.4.1 Solutions that help adapt to and mitigate climate change while contributing to combating desertification are site and regionally specific and include *inter alia*: water harvesting and micro-irrigation, restoring degraded lands using drought-resilient ecologically appropriate plants, agroforestry, and other agroecological and ecosystem-based adaptation practices (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5, 5.2, 5.6}

B.4.2 Reducing dust and sand storms and sand dune movement can lessen the negative effects of wind erosion and improve air quality and health (*high confidence*). Depending on water availability and soil conditions, afforestation, tree planting and ecosystem restoration programs, which aim for the creation of windbreaks in the form of 'green walls' and 'green dams' using native and other climate resilient tree species with low water needs, can reduce sand storms, avert wind erosion, and contribute to carbon sinks, while improving micro-climates, soil nutrients and water retention (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5}

B.4.3 Measures to combat desertification can promote soil carbon sequestration (*high confidence*). Natural vegetation restoration and tree planting on degraded land enriches, in the long term, carbon in the topsoil and subsoil (*medium confidence*). Modelled rates of carbon sequestration following the adoption of conservation agriculture practices in drylands depend on local conditions (*medium confidence*). If soil carbon is lost, it may take a prolonged period of time for carbon stocks to recover. {3.1.4, 3.3, 3.6.1, 3.6.3, 3.7.1, 3.7.2}

B.4.4 Eradicating poverty and ensuring food security can benefit from applying measures promoting land degradation neutrality (including avoiding, reducing and reversing land degradation) in rangelands, croplands and forests, which contribute to combating desertification, while mitigating and adapting to climate change within the framework of sustainable development. Such measures include avoiding deforestation and locally suitable practices including management of rangeland and forest fires (*high confidence*). {3.4.2, 3.6.1, 3.6.2, 3.6.3, 4.8.5}

B.4.5 Currently there is a lack of knowledge of adaptation limits and potential maladaptation to combined effects of climate change and desertification. In the absence of new or enhanced adaptation options, the potential for residual risks and maladaptive outcomes is high (*high confidence*). Even when solutions are available, social, economic and institutional constraints could pose barriers to their implementation (*medium confidence*). Some adaptation options can become maladaptive due to their environmental impacts, such as irrigation causing soil salinisation or over extraction leading to ground-water depletion (*medium confidence*). Extreme forms of desertification can lead to the complete loss of land productivity, limiting adaptation options or reaching the limits to adaptation (*high confidence*). {Executive Summary Chapter 3, 3.6.4, 3.7.5, 7.4.9}

B.4.6 Developing, enabling and promoting access to cleaner energy sources and technologies can contribute to adaptation and mitigating climate change and combating desertification and forest degradation through decreasing the use of traditional biomass for energy while increasing the diversity of energy supply (*medium confidence*). This can have socioeconomic and health benefits, especially for women and children. (*high confidence*). The efficiency of wind and solar energy infrastructures is recognised; the efficiency can be affected in some regions by dust and sand storms (*high confidence*). {3.5.3, 3.5.4, 4.4.4, 7.5.2, Cross-Chapter Box 12 in Chapter 7}

B.5 Sustainable land management,[33] including sustainable forest management,[34] can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation (*very high confidence*). It can also contribute to mitigation and adaptation (*high confidence*). Reducing and reversing land degradation, at scales from individual farms to entire watersheds, can provide cost effective, immediate, and long-term benefits to communities and support several Sustainable Development Goals (SDGs) with co-benefits for adaptation (*very high confidence*) and mitigation (*high confidence*). Even with implementation of sustainable land management, limits to adaptation can be exceeded in some situations (*medium confidence*). {1.3.2, 4.1.5, 4.8, 7.5.6, Table 4.2}

B.5.1 Land degradation in agriculture systems can be addressed through sustainable land management, with an ecological and socioeconomic focus, with co-benefits for climate change adaptation. Management options that reduce vulnerability to soil erosion and nutrient loss include growing green manure crops and cover crops, crop residue retention, reduced/zero tillage, and maintenance of ground cover through improved grazing management (*very high confidence*). {4.8}

B.5.2 The following options also have mitigation co-benefits. Farming systems such as agroforestry, perennial pasture phases and use of perennial grains, can substantially reduce erosion and nutrient leaching while building soil carbon (*high confidence*). The global sequestration potential of cover crops would be about 0.44 ± 0.11 $GtCO_2$ yr^{-1} if applied to 25% of global cropland (*high confidence*). The application of certain biochars can sequester carbon (*high confidence*), and improve soil conditions in some soil types/climates (*medium confidence*). {4.8.1.1, 4.8.1.3, 4.9.2, 4.9.5, 5.5.1, 5.5.4, Cross-Chapter Box 6 in Chapter 5}

B.5.3 Reducing deforestation and forest degradation lowers GHG emissions (*high confidence*), with an estimated technical mitigation potential of 0.4–5.8 $GtCO_2$ yr^{-1}. By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) (*high confidence*). Sustainable forest management aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem functions and services, can lower GHG emissions and can contribute to adaptation (*high confidence*). {2.6.1.2, 4.1.5, 4.3.2, 4.5.3, 4.8.1.3, 4.8.3, 4.8.4}

B.5.4 Sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest carbon sinks, including by transferring carbon to wood products, thus addressing the issue of sink saturation (*high confidence*). Where wood carbon is transferred to harvested wood products, these can store carbon over the long-term and can substitute for emissions-intensive materials reducing emissions in other sectors (*high confidence*). Where biomass is used for energy, e.g., as a mitigation strategy, the carbon is released back into the atmosphere more quickly (*high confidence*). (Figure SPM.3) {2.6.1, 2.7, 4.1.5, 4.8.4, 6.4.1, Cross-Chapter Box 7 in Chapter 6}

B.5.5 Climate change can lead to land degradation, even with the implementation of measures intended to avoid, reduce or reverse land degradation (*high confidence*). Such limits to adaptation are dynamic, site-specific and are determined through the interaction of biophysical changes with social and institutional conditions (*very high confidence*). In some situations, exceeding the limits of adaptation can trigger escalating losses or result in undesirable transformational changes (*medium confidence*) such as forced migration (*low confidence*), conflicts (*low confidence*) or poverty (*medium confidence*). Examples of climate change induced land degradation that may exceed limits to adaptation include coastal erosion exacerbated by sea level rise where land disappears (*high confidence*), thawing of permafrost affecting infrastructure and livelihoods (*medium confidence*), and extreme soil erosion causing loss of productive capacity (*medium confidence*). {4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8}

B.6 Response options throughout the food system, from production to consumption, including food loss and waste, can be deployed and scaled up to advance adaptation and mitigation (*high confidence*). The total technical mitigation potential from crop and livestock activities, and agroforestry is estimated as 2.3 – 9.6 $GtCO_2eq$ yr^{-1} by 2050 (*medium confidence*). The total technical mitigation potential of dietary changes is estimated as 0.7 – 8 $GtCO_2eq$ yr^{-1} by 2050 (*medium confidence*). {5.3, 5.5, 5.6}

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[33] Sustainable land management is defined in this report as 'the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions'. Examples of options include, *inter alia*, agroecology (including agroforestry), conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the conservation of pollinators, rain water harvesting, range and pasture management, and precision agriculture systems.

[34] Sustainable forest management is defined in this report as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfil now and in the future, relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems'.

B.6.1 Practices that contribute to climate change adaptation and mitigation in cropland include increasing soil organic matter, erosion control, improved fertiliser management, improved crop management, for example paddy rice management, and use of varieties and genetic improvements for heat and drought tolerance. For livestock, options include better grazing land management, improved manure management, higher-quality feed, and use of breeds and genetic improvement. Different farming and pastoral systems can achieve reductions in the emissions intensity of livestock products. Depending on the farming and pastoral systems and level of development, reductions in the emissions intensity of livestock products may lead to absolute reductions in GHG emissions (*medium confidence*). Many livestock related options can enhance the adaptive capacity of rural communities, in particular, of smallholders and pastoralists. Significant synergies exist between adaptation and mitigation, for example through sustainable land management approaches (*high confidence*). {4.8, 5.3.3, 5.5.1, 5.6}

B.6.2 Diversification in the food system (e.g., implementation of integrated production systems, broad-based genetic resources, and diets) can reduce risks from climate change (*medium confidence*). Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, present major opportunities for adaptation and mitigation while generating significant co-benefits in terms of human health (*high confidence*). By 2050, dietary changes could free several million km^2 (*medium confidence*) of land and provide a technical mitigation potential of 0.7 to 8.0 $GtCO_2eq\ yr^{-1}$, relative to business as usual projections (*high confidence*). Transitions towards low-GHG emission diets may be influenced by local production practices, technical and financial barriers and associated livelihoods and cultural habits (*high confidence*). {5.3, 5.5.2, 5.5, 5.6}

B.6.3 Reduction of food loss and waste can lower GHG emissions and contribute to adaptation through reduction in the land area needed for food production (*medium confidence*). During 2010-2016, global food loss and waste contributed 8 –10% of total anthropogenic GHG emissions (*medium confidence*). Currently, 25 –30% of total food produced is lost or wasted (*medium confidence*). Technical options such as improved harvesting techniques, on-farm storage, infrastructure, transport, packaging, retail and education can reduce food loss and waste across the supply chain. Causes of food loss and waste differ substantially between developed and developing countries, as well as between regions (*medium confidence*). By 2050, reduced food loss and waste can free several million km^2 of land (*low confidence*). {5.5.2, 6.3.6}

B.7 Future land use depends, in part, on the desired climate outcome and the portfolio of response options deployed (*high confidence*). All assessed modelled pathways that limit warming to 1.5°C or well below 2°C require land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy (*high confidence*). A small number of modelled pathways achieve 1.5°C with reduced land conversion (*high confidence*) and thus reduced consequences for desertification, land degradation, and food security (*medium confidence*). (Figure SPM.4) {2.6, 6.4, 7.4, 7.6, Cross-Chapter Box 9 in Chapter 6}

B.7.1 Modelled pathways limiting global warming to 1.5°C[35] include more land-based mitigation than higher warming level pathways (*high confidence*), but the impacts of climate change on land systems in these pathways are less severe (*medium confidence*). (Figure SPM.2, Figure SPM.4) {2.6, 6.4, 7.4, Cross-Chapter Box 9 in Chapter 6}

B.7.2 Modelled pathways limiting global warming to 1.5°C and 2°C project a 2 million km^2 reduction to a 12 million km^2 increase in forest area in 2050 relative to 2010 (*medium confidence*). 3°C pathways project lower forest areas, ranging from a 4 million km^2 reduction to a 6 million km^2 increase (*medium confidence*). (Figure SPM.3, Figure SPM.4) {2.5, 6.3, 7.3, 7.5, Cross-Chapter Box 9 in Chapter 6}

B.7.3 The land area needed for bioenergy in modelled pathways varies significantly depending on the socio-economic pathway, the warming level, and the feedstock and production system used (*high confidence*). Modelled pathways limiting global warming to 1.5°C use up to 7 million km^2 for bioenergy in 2050; bioenergy land area is smaller in 2°C (0.4 to 5 million km^2) and 3°C pathways (0.1 to 3 million km^2) (*medium confidence*). Pathways with large levels of land conversion may imply adverse side-effects impacting water scarcity, biodiversity, land degradation, desertification, and food security, if not adequately and carefully managed, whereas best practice implementation at appropriate scales can have co-benefits, such as management of dryland salinity, enhanced biocontrol and biodiversity and enhancing soil carbon sequestration (*high confidence*). (Figure SPM.3) {2.6, 6.1, 6.4, 7.2, Cross-Chapter Box 7 in Chapter 6}

[35] In this report references to pathways limiting global warming to a particular level are based on a 66% probability of staying below that temperature level in 2100 using the MAGICC model.

B.7.4 Most mitigation pathways include substantial deployment of bioenergy technologies. A small number of modelled pathways limit warming to 1.5ºC with reduced dependence on bioenergy and BECCS (land area below <1 million km^2 in 2050) and other carbon dioxide removal (CDR) options (*high confidence*). These pathways have even more reliance on rapid and far-reaching transitions in energy, land, urban systems and infrastructure, and on behavioural and lifestyle changes compared to other 1.5°C pathways. {2.6.2, 5.5.1, 6.4, Cross-Chapter Box 7 in Chapter 6}

B.7.5 These modelled pathways do not consider the effects of climate change on land or CO_2 fertilisation. In addition, these pathways include only a subset of the response options assessed in this report (*high confidence*); the inclusion of additional response options in models could reduce the projected need for bioenergy or CDR that increases the demand for land. {6.4.4, Cross-Chapter Box 9 in Chapter 6}

SPM

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel A shows response options that can be implemented without or with limited competition for land, including some that have the potential to reduce the demand for land. Co-benefits and adverse side effects are shown quantitatively based on the high end of the range of potentials assessed. Magnitudes of contributions are categorised using thresholds for positive or negative impacts. Letters within the cells indicate confidence in the magnitude of the impact relative to the thresholds used (see legend). Confidence in the direction of change is generally higher.

	Response options based on land management	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Agriculture	Increased food productivity	L	M	L	M	H	——
	Agro-forestry	M	M	M	M	L	●
	Improved cropland management	M	L	L	L	L	●●
	Improved livestock management	M	L	L	L	L	●●●
	Agricultural diversification	L	L	L	M	L	●
	Improved grazing land management	M	L	L	L	L	——
	Integrated water management	L	L	L	L	L	●●
	Reduced grassland conversion to cropland	L	——	L	L	- L	●
Forests	Forest management	M	L	L	L	L	●●
	Reduced deforestation and forest degradation	H	L	L	L	L	●●
Soils	Increased soil organic carbon content	H	L	M	M	L	●●
	Reduced soil erosion	←→ L	L	M	M	L	●●
	Reduced soil salinization	——	L	L	L	L	●●
	Reduced soil compaction	——	L	——	L	L	●
Other ecosystems	Fire management	M	M	M	M	L	●
	Reduced landslides and natural hazards	L	L	L	L	L	——
	Reduced pollution including acidification	←→ M	M	L	L	L	——
	Restoration & reduced conversion of coastal wetlands	M	L	M	M	←→ L	——
	Restoration & reduced conversion of peatlands	M	——	na	M	- L	●
	Response options based on value chain management						
Demand	Reduced post-harvest losses	H	M	L	L	H	——
	Dietary change	H	——	L	H	H	——
	Reduced food waste (consumer or retailer)	H	——	L	M	M	——
Supply	Sustainable sourcing	——	L	——	L	L	——
	Improved food processing and retailing	L	L	——	——	L	——
	Improved energy use in food systems	L	L	——	——	L	——
	Response options based on risk management						
Risk	Livelihood diversification	——	L	——	L	L	——
	Management of urban sprawl	——	L	L	M	L	——
	Risk sharing instruments	←→ L	L	——	←→ L	L	●●

Options shown are those for which data are available to assess global potential for three or more land challenges.
The magnitudes are assessed independently for each option and are not additive.

Key for criteria used to define magnitude of impact of each integrated response option

		Mitigation *Gt CO_2-eq yr^{-1}*	Adaptation *Million people*	Desertification *Million km²*	Land Degradation *Million km²*	Food Security *Million people*
Positive	Large	More than 3	Positive for more than 25	Positive for more than 3	Positive for more than 3	Positive for more than 100
	Moderate	0.3 to 3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
	Small	Less than 0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	Negligible	No effect	No effect	No effect	No effect	No effect
Negative	- Small	Less than -0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	- Moderate	-0.3 to -3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
	- Large	More than -3	Negative for more than 25	Negative for more than 3	Negative for more than 3	Negative for more than 100

←→ **Variable:** Can be positive or negative   —— no data   na not applicable

Confidence level

Indicates confidence in the estimate of magnitude category.

H *High confidence*
M *Medium confidence*
L *Low confidence*

Cost range

See technical caption for cost ranges in US\$ tCO_2e^{-1} or US\$ ha^{-1}.

●●● High cost
●● Medium cost
● Low cost
—— no data

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel B shows response options that rely on additional land-use change and could have implications across three or more land challenges under different implementation contexts. For each option, the first row (high level implementation) shows a quantitative assessment (as in Panel A) of implications for global implementation at scales delivering CO_2 removals of more than 3 $GtCO_2$ yr^{-1} using the magnitude thresholds shown in Panel A. The red hatched cells indicate an increasing pressure but unquantified impact. For each option, the second row (best practice implementation) shows qualitative estimates of impact if implemented using best practices in appropriately managed landscape systems that allow for efficient and sustainable resource use and supported by appropriate governance mechanisms. In these qualitative assessments, green indicates a positive impact, grey indicates a neutral interaction.

Bioenergy and BECCS

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
H	L			L	● / ●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts, assuming carbon dioxide removal by BECCS at a scale of 11.3 $GtCO_2$ yr^{-1} in 2050, and noting that bioenergy without CCS can also achieve emissions reductions of up to several $GtCO_2$ yr^{-1} when it is a low carbon energy source {2.6.1; 6.3.1}. Studies linking bioenergy to food security estimate an increase in the population at risk of hunger to up to 150 million people at this level of implementation {6.3.5}. The red hatched cells for desertification and land degradation indicate that while up to 15 million km^2 of additional land is required in 2100 in 2°C scenarios which will increase pressure for desertification and land degradation, the actual area affected by this additional pressure is not easily quantified {6.3.3; 6.3.4}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: The sign and magnitude of the effects of bioenergy and BECCS depends on the scale of deployment, the type of bioenergy feedstock, which other response options are included, and where bioenergy is grown (including prior land use and indirect land use change emissions). For example, limiting bioenergy production to marginal lands or abandoned cropland would have negligible effects on biodiversity, food security, and potentially co-benefits for land degradation; however, the benefits for mitigation could also be smaller. {Table 6.58}

Reforestation and forest restoration

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	M	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of reforestation and forest restoration (partly overlapping with afforestation) at a scale of 10.1 $GtCO_2$ yr^{-1} removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people; the impact of reforestation is lower {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: There are co-benefits of reforestation and forest restoration in previously forested areas, assuming small scale deployment using native species and involving local stakeholders to provide a safety net for food security. Examples of sustainable implementation include, but are not limited to, reducing illegal logging and halting illegal forest loss in protected areas, reforesting and restoring forests in degraded and desertified lands {Box6.1C; Table 6.6}.

Afforestation

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	M	M	L	M	●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of afforestation (partly overlapping with reforestation and forest restoration) at a scale of 8.9 $GtCO_2$ yr^{-1} removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: Afforestation is used to prevent desertification and to tackle land degradation. Forested land also offers benefits in terms of food supply, especially when forest is established on degraded land, mangroves, and other land that cannot be used for agriculture. For example, food from forests represents a safety-net during times of food and income insecurity {6.3.5}.

Biochar addition to soil

Mitigation	Adaptation	Desertification	Land degradation	Food security	Cost
M	—	—	L	L	●●●

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of biochar at a scale of 6.6 $GtCO_2$ yr^{-1} removal {6.3.1}. Dedicated biomass crops required for feedstock production could occupy 0.4–2.6 Mkm^2 of land, equivalent to around 20% of the global cropland area, which could potentially have a large effect on food security for up to 100 million people {6.3.5}.

Mitigation	Adaptation	Desertification	Land degradation	Food security

Best practice: When applied to land, biochar could provide moderate benefits for food security by improving yields by 25% in the tropics, but with more limited impacts in temperate regions, or through improved water holding capacity and nutrient use efficiency. Abandoned cropland could be used to supply biomass for biochar, thus avoiding competition with food production; 5-9 Mkm^2 of land is estimated to be available for biomass production without compromising food security and biodiversity, considering marginal and degraded land and land released by pasture intensification {6.3.5}.

SPM

Figure SPM.3: Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security. | This Figure is based on an aggregation of information from studies with a wide variety of assumptions about how response options are implemented and the contexts in which they occur. Response options implemented differently at local to global scales could lead to different outcomes. **Magnitude of potential:** For panel A, magnitudes are for the technical potential of response options globally. For each land challenge, magnitudes are set relative to a marker level as follows. For mitigation, potentials are set relative to the approximate potentials for the response options with the largest individual impacts (~3 $GtCO_2$-eq yr^{-1}). The threshold for the 'large' magnitude category is set at this level. For adaptation, magnitudes are set relative to the 100 million lives estimated to be affected by climate change and a carbon-based economy between 2010 and 2030. The threshold for the 'large' magnitude category represents 25% of this total. For desertification and land degradation, magnitudes are set relative to the lower end of current estimates of degraded land, 10–60 million km^2. The threshold for the 'large' magnitude category represents 30% of the lower estimate. For food security, magnitudes are set relative to the approximately 800 million people who are currently undernourished. The threshold for the 'large' magnitude category represents 12.5% of this total. For panel B, for the first row (high level implementation) for each response option, the magnitude and thresholds are as defined for panel A. In the second row (best practice implementation) for each response option, the qualitative assessments that are green denote potential positive impacts, and those shown in grey indicate neutral interactions. Increased food production is assumed to be achieved through sustainable intensification rather than through injudicious application of additional external inputs such as agrochemicals. **Levels of confidence:** Confidence in the magnitude category (high, medium or low) into which each option falls for mitigation, adaptation, combating desertification and land degradation, and enhancing food security. *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:** Cost estimates are based on aggregation of often regional studies and vary in the components of costs that are included. In panel B, cost estimates are not provided for best practice implementation. One coin indicates low cost (<USD10 tCO_2-eq^{-1} or <USD20 ha^{-1}), two coins indicate medium cost (USD10-USD100 tCO_2-eq^{-1} or USD20 –USD200 ha^{-1}), and three coins indicate high cost (>USD100 tCO_2-eq^{-1} or USD200 ha^{-1}). Thresholds in USD 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 quantitative potential for land management-based response options can be found as follows: for mitigation Table's 6.13 to 6.20, with further evidence in Section 2.7.1; for adaptation Table's 6.21 to 6.28; for combating desertification Table's 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 Table's 6.45 to 6.52, with further evidence in Chapter 5. Other synergies and trade-offs not shown here are discussed in Chapter 6. Additional supporting evidence for the qualitative assessments in the second row for each option in panel B can be found in the Table's 6.6, 6.55, 6.56 and 6.58, Section 6.3.5.1.3, and Box 6.1c.

C. Enabling response options

C.1 Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways (*high confidence*). Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster engagement and collaboration between multiple stakeholders (*high confidence*). (Figure SPM.1, Figure SPM.2, Figure SPM.3) {3.6.2, 3.6.3, 4.8, 4.9.4, 5.7, 6.3, 6.4, 7.2.2, 7.3, 7.4, 7.4.7, 7.4.8, 7.5, 7.5.5, 7.5.6, 7.6.6, Cross-Chapter Box 10 in Chapter 7}

C.1.1 Land-use zoning, spatial planning, integrated landscape planning, regulations, incentives (such as payment for ecosystem services), and voluntary or persuasive instruments (such as environmental farm planning, standards and certification for sustainable production, use of scientific, local and indigenous knowledge and collective action), can achieve positive adaptation and mitigation outcomes (*medium confidence*). They can also contribute revenue and provide incentive to rehabilitate degraded lands and adapt to and mitigate climate change in certain contexts (*medium confidence*). Policies promoting the target of land degradation neutrality can also support food security, human wellbeing and climate change adaptation and mitigation (*high confidence*). (Figure SPM.2) {3.4.2, 4.1.6, 4.7, 4.8.5, 5.1.2, 5.7.3, 7.3, 7.4.6, 7.4.7, 7.5}

C.1.2 Insecure land tenure affects the ability of people, communities and organisations to make changes to land that can advance adaptation and mitigation (*medium confidence*). Limited recognition of customary access to land and ownership of land can result in increased vulnerability and decreased adaptive capacity (*medium confidence*). Land policies (including recognition of customary tenure, community mapping, redistribution, decentralisation, co-management, regulation of rental markets) can provide both security and flexibility response to climate change (*medium confidence*). {3.6.1, 3.6.2, 5.3, 7.2.4, 7.6.4, Cross-Chapter Box 6 in Chapter 5}

C.1.3 Achieving land degradation neutrality will involve a balance of measures that avoid and reduce land degradation, through adoption of sustainable land management, and measures to reverse degradation through rehabilitation and restoration of degraded land. Many interventions to achieve land degradation neutrality commonly also deliver climate change adaptation and mitigation benefits. The pursuit of land degradation neutrality provides impetus to address land degradation and climate change simultaneously (*high confidence*). {4.5.3, 4.8.5, 4.8.7, 7.4.5}

C.1.4 Due to the complexity of challenges and the diversity of actors involved in addressing land challenges, a mix of policies, rather than single policy approaches, can deliver improved results in addressing the complex challenges of sustainable land management and climate change (*high confidence*). Policy mixes can strongly reduce the vulnerability and exposure of human and natural systems to climate change (*high confidence*). Elements of such policy mixes may include weather and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, universal access to early warning systems combined with effective contingency plans (*high confidence*). (Figure SPM.4) {1.2, 4.8, 4.9.2, 5.3.2, 5.6, 5.6.6, 5.7.2, 7.3.2, 7.4, 7.4.2, 7.4.6, 7.4.7, 7.4.8, 7.5.5, 7.5.6, 7.6.4}

C.2 Policies that operate across the food system, including those that reduce food loss and waste and influence dietary choices, enable more sustainable land-use management, enhanced food security and low emissions trajectories (*high confidence*). Such policies can contribute to climate change adaptation and mitigation, reduce land degradation, desertification and poverty as well as improve public health (*high confidence*). The adoption of sustainable land management and poverty eradication can be enabled by improving access to markets, securing land tenure, factoring environmental costs into food, making payments for ecosystem services, and enhancing local and community collective action (*high confidence*). {1.1.2, 1.2.1, 3.6.3, 4.7.1, 4.7.2, 4.8, 5.5, 6.4, 7.4.6, 7.6.5}

C.2.1 Policies that enable and incentivise sustainable land management for climate change adaptation and mitigation include improved access to markets for inputs, outputs and financial services, empowering women and indigenous peoples, enhancing local and community collective action, reforming subsidies and promoting an enabling trade system (*high confidence*). Land restoration and rehabilitation efforts can be more effective when policies support local management of natural resources, while strengthening cooperation between actors and institutions, including at the international level. {3.6.3, 4.1.6, 4.5.4, 4.8.2, 4.8.4, 5.7, 7.2, 7.3}

C.2.2 Reflecting the environmental costs of land-degrading agricultural practices can incentivise more sustainable land management (*high confidence*). Barriers to the reflection of environmental costs arise from technical difficulties in estimating these costs and those embodied in foods. {3.6.3, 5.5.1, 5.5.2, 5.6.6, 5.7, 7.4.4, Cross-Chapter Box 10 in Chapter 7}

C.2.3 Adaptation and enhanced resilience to extreme events impacting food systems can be facilitated by comprehensive risk management, including risk sharing and transfer mechanisms (*high confidence*). Agricultural diversification, expansion of market access, and preparation for increasing supply chain disruption can support the scaling up of adaptation in food systems (*high confidence*). {5.3.2, 5.3.3, 5.3.5}

C.2.4 Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, health insurance, financial incentives, and awareness-raising campaigns, can potentially influence food demand, reduce healthcare costs, contribute to lower GHG emissions and enhance adaptive capacity (*high confidence*). Influencing demand for food, through promoting diets based on public health guidelines, can enable more sustainable land management and contribute to achieving multiple SDGs (*high confidence*). {3.4.2, 4.7.2, 5.1, 5.7, 6.3, 6.4}

C.3 Acknowledging co-benefits and trade-offs when designing land and food policies can overcome barriers to implementation (*medium confidence*). Strengthened multi-level, hybrid and cross-sectoral governance, as well as policies developed and adopted in an iterative, coherent, adaptive and flexible manner can maximise co-benefits and minimise trade-offs, given that land management decisions are made from farm level to national scales, and both climate and land policies often range across multiple sectors, departments and agencies (*high confidence*). (Figure SPM.3) {4.8.5, 4.9, 5.6, 6.4, 7.3, 7.4.6, 7.4.8, 7.4.9, 7.5.6, 7.6.2}

C.3.1 Addressing desertification, land degradation, and food security in an integrated, coordinated and coherent manner can assist climate resilient development and provides numerous potential co-benefits (*high confidence*). {3.7.5, 4.8, 5.6, 5.7, 6.4, 7.2.2, 7.3.1, 7.3.4, 7.4.7, 7.4.8, 7.5.6, 7.5.5}

C.3.2 Technological, biophysical, socio-economic, financial and cultural barriers can limit the adoption of many land-based response options, as can uncertainty about benefits (*high confidence*). Many sustainable land management practices are not widely adopted due to insecure land tenure, lack of access to resources and agricultural advisory services, insufficient and unequal private and public incentives, and lack of knowledge and practical experience (*high confidence*). Public discourse, carefully designed policy interventions, incorporating social learning and market changes can together help reduce barriers to implementation (*medium confidence*). {3.6.1, 3.6.2, 5.3.5, 5.5.2, 5.6, 6.2, 6.4, 7.4, 7.5, 7.6}

C.3.3 The land and food sectors face particular challenges of institutional fragmentation and often suffer from a lack of engagement between stakeholders at different scales and narrowly focused policy objectives (*medium confidence*). Coordination with other sectors, such as public health, transportation, environment, water, energy and infrastructure, can increase co-benefits, such as risk reduction and improved health (*medium confidence*). {5.6.3, 5.7, 6.2, 6.4.4, 7.1, 7.3, 7.4.8, 7.6.2, 7.6.3}

C.3.4 Some response options and policies may result in trade-offs, including social impacts, ecosystem functions and services damage, water depletion, or high costs, that cannot be well-managed, even with institutional best practices (*medium confidence*). Addressing such trade-offs helps avoid maladaptation (*medium confidence*). Anticipation and evaluation of potential trade-offs and knowledge gaps supports evidence-based policymaking to weigh the costs and benefits of specific responses for different stakeholders (*medium confidence*). Successful management of trade-offs often includes maximising stakeholder input with structured feedback processes, particularly in community-based models, use of innovative fora like facilitated dialogues or spatially explicit mapping, and iterative adaptive management that allows for continuous readjustments in policy as new evidence comes to light (*medium confidence*). {5.3.5, 6.4.2, 6.4.4, 6.4.5, 7.5.6, Cross-Chapter Box 9 in Chapter 7}

C.4 The effectiveness of decision-making and governance is enhanced by the involvement of local stakeholders (particularly those most vulnerable to climate change including indigenous peoples and local communities, women, and the poor and marginalised) in the selection, evaluation, implementation and monitoring of policy instruments for land-based climate change adaptation and mitigation (*high confidence*). Integration across sectors and scales increases the chance of maximising co-benefits and minimising trade-offs (*medium confidence*). {1.4, 3.1, 3.6, 3.7, 4.8, 4.9, 5.1.3, Box 5.1, 7.4, 7.6}

C.4.1 Successful implementation of sustainable land management practices requires accounting for local environmental and socio-economic conditions (*very high confidence*). Sustainable land management in the context of climate change is typically advanced by involving all relevant stakeholders in identifying land-use pressures and impacts (such as biodiversity decline, soil loss, over-extraction of groundwater, habitat loss, land-use change in agriculture, food production and forestry) as well as preventing, reducing and restoring degraded land (*medium confidence*). {1.4.1, 4.1.6, 4.8.7, 5.2.5, 7.2.4, 7.6.2, 7.6.4}

C.4.2 Inclusiveness in the measurement, reporting and verification of the performance of policy instruments can support sustainable land management (*medium confidence*). Involving stakeholders in the selection of indicators, collection of climate data, land modelling and land-use planning, mediates and facilitates integrated landscape planning and choice of policy (*medium confidence*). {3.7.5, 5.7.4, 7.4.1, 7.4.4, 7.5.3, 7.5.4, 7.5.5, 7.6.4, 7.6.6}

C.4.3 Agricultural practices that include indigenous and local knowledge can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation (*high confidence*). Coordinated action across a range of actors including businesses, producers, consumers, land managers and policymakers in partnership with indigenous peoples and local communities enable conditions for the adoption of response options (*high confidence*) {3.1.3, 3.6.1, 3.6.2, 4.8.2, 5.5.1, 5.6.4, 5.7.1, 5.7.4, 6.2, 7.3, 7.4.6, 7.6.4}

C.4.4 Empowering women can bring synergies and co-benefits to household food security and sustainable land management (*high confidence*). Due to women's disproportionate vulnerability to climate change impacts, their inclusion in land management and tenure is constrained. Policies that can address land rights and barriers to women's participation in sustainable land management include financial transfers to women under the auspices of anti-poverty programmes, spending on health, education, training and capacity building for women, subsidised credit and program dissemination through existing women's community-based organisations (*medium confidence*). {1.4.1, 4.8.2, 5.1.3, Cross-Chapter Box 11 in Chapter 7}

SPM

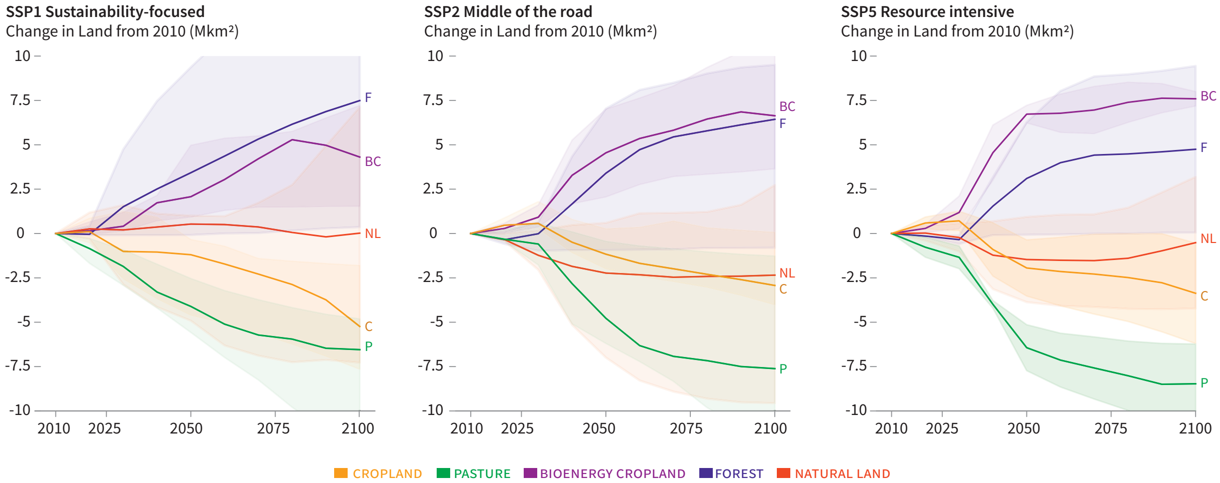
A. Pathways linking socioeconomic development, mitigation responses and land

Socioeconomic development and land management influence the evolution of the land system including the relative amount of land allocated to **CROPLAND**, **PASTURE**, **BIOENERGY CROPLAND**, **FOREST**, and **NATURAL LAND**. The lines show the median across Integrated Assessment Models (IAMs) for three alternative shared socioeconomic pathways (**SSP1**, **SSP2** and **SSP5** at **RCP1.9**); shaded areas show the range across models. Note that pathways illustrate the effects of climate change mitigation but not those of climate change impacts or adaptation.

A. Sustainability-focused (SSP1)
Sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation, and bioenergy.

B. Middle of the road (SSP2)
Societal as well as technological development follows historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre.

C. Resource intensive (SSP5)
Resource-intensive production and consumption patterns, results in high baseline emissions. Mitigation focuses on technological solutions including substantial bioenergy and BECCS . Intensification and competing land uses contribute to declines in agricultural land.



B. Land use and land cover change in the SSPs

	Quantitative indicators for the SSPs	Count of models included*	Change in Natural Land from 2010 Mkm²	Change in Bioenergy Cropland from 2010 Mkm²	Change in Cropland from 2010 Mkm²	Change in Forest from 2010 Mkm²	Change in Pasture from 2010 Mkm²
SSP1	**RCP1.9** in 2050	5/5	0.5 (-4.9, 1)	2.1 (0.9, 5)	-1.2 (-4.6, -0.3)	3.4 (-0.1, 9.4)	-4.1 (-5.6, -2.5)
	↳ 2100		0 (-7.3, 7.1)	4.3 (1.5, 7.2)	-5.2 (-7.6, -1.8)	7.5 (0.4, 15.8)	-6.5 (-12.2, -4.8)
	RCP2.6 in 2050	5/5	-0.9 (-2.2, 1.5)	1.3 (0.4, 1.9)	-1 (-4.7, 1)	2.6 (-0.1, 8.4)	-3 (-4, -2.4)
	↳ 2100		0.2 (-3.5, 1.1)	5.1 (1.6, 6.3)	-3.2 (-7.7, -1.8)	6.6 (-0.1, 10.5)	-5.5 (-9.9, -4.2)
	RCP4.5 in 2050	5/5	0.5 (-1, 1.7)	0.8 (0.5, 1.3)	0.1 (-3.2, 1.5)	0.6 (-0.7, 4.2)	-2.4 (-3.3, -0.9)
	↳ 2100		1.8 (-1.7, 6)	1.9 (1.4, 3.7)	-2.3 (-6.4, -1.6)	3.9 (0.2, 8.8)	-4.6 (-7.3, -2.7)
	Baseline in 2050	5/5	0.3 (-1.1, 1.8)	0.5 (0.2, 1.4)	0.2 (-1.6, 1.9)	-0.1 (-0.8, 1.1)	-1.5 (-2.9, -0.2)
	↳ 2100		3.3 (-0.3, 5.9)	1.8 (1.4, 2.4)	-1.5 (-5.7, -0.9)	0.9 (0.3, 3)	-2.1 (-7, 0)
SSP2	**RCP1.9** in 2050	4/5	-2.2 (-7, 0.6)	4.5 (2.1, 7)	-1.2 (-2, 0.3)	3.4 (-0.9, 7)	-4.8 (-6.2, -0.4)
	↳ 2100		-2.3 (-9.6, 2.7)	6.6 (3.6, 11)	-2.9 (-4, 0.1)	6.4 (-0.8, 9.5)	-7.6 (-11.7, -1.3)
	RCP2.6 in 2050	5/5	-3.2 (-4.2, 0.1)	2.2 (1.7, 4.7)	0.6 (-1.9, 1.9)	1.6 (-0.9, 4.2)	-1.4 (-3.7, 0.4)
	↳ 2100		-5.2 (-7.2, 0.5)	6.9 (2.3, 10.8)	-1.4 (-4, 0.8)	5.6 (-0.9, 5.9)	-7.2 (-8, 0.5)
	RCP4.5 in 2050	5/5	-2.2 (-2.2, 0.7)	1.5 (0.1, 2.1)	1.2 (-0.9, 2.7)	-0.9 (-2.5, 2.9)	-0.1 (-2.5, 1.6)
	↳ 2100		-3.4 (-4.7, 1.5)	4.1 (0.4, 6.3)	0.7 (-2.6, 3.1)	-0.5 (-3.1, 5.9)	-2.8 (-5.3, 1.9)
	Baseline in 2050	5/5	-1.5 (-2.6, -0.2)	0.7 (0, 1.5)	1.3 (1, 2.7)	-1.3 (-2.5, -0.4)	-0.1 (-1.2, 1.6)
	↳ 2100		-2.1 (-5.9, 0.3)	1.2 (0.1, 2.4)	1.9 (0.8, 2.8)	-1.3 (-2.7, -0.2)	-0.2 (-1.9, 2.1)
SSP3	**RCP1.9** in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	Infeasible in all assessed models		-	-	-	-
	↳ 2100			-	-	-	-
	RCP4.5 in 2050	3/3	-3.4 (-4.4, -2)	1.3 (1.3, 2)	2.3 (1.2, 3)	-2.4 (-4, -1)	2.1 (-0.1, 3.8)
	↳ 2100		-6.2 (-6.8, -5.4)	4.6 (1.5, 7.1)	3.4 (1.9, 4.5)	-3.1 (-5.5, -0.3)	2 (-2.5, 4.4)
	Baseline in 2050	4/4	-3 (-4.6, -1.7)	1 (0.2, 1.5)	2.5 (1.5, 3)	-2.5 (-4, -1.5)	2.4 (0.6, 3.8)
	↳ 2100		-5 (-7.1, -4.2)	1.1 (0.9, 2.5)	5.1 (3.8, 6.1)	-5.3 (-6, -2.6)	3.4 (0.9, 6.4)
SSP4	**RCP1.9** in 2050	Infeasible in all assessed models**		-	-	-	-
	↳ 2100			-	-	-	-
	RCP2.6 in 2050	3/3	-4.5 (-6, -2.1)	3.3 (1.5, 4.5)	0.5 (-0.1, 0.9)	0.7 (-0.3, 2.2)	-0.6 (-0.7, 0.1)
	↳ 2100		-5.8 (-10.2, -4.7)	2.5 (2.3, 15.2)	-0.8 (-0.8, 1.8)	1.4 (-1.7, 4.1)	-1.2 (-2.5, -0.2)
	RCP4.5 in 2050	3/3	-2.7 (-4.4, -0.4)	1.7 (1, 1.9)	1.1 (-0.1, 1.7)	-1.8 (-2.3, 2.1)	0.8 (-0.5, 1.5)
	↳ 2100		-2.8 (-7.8, -2)	2.7 (2.3, 4.7)	1.1 (0.2, 1.2)	-0.7 (-2.6, 1)	1.4 (-1, 1.8)
	Baseline in 2050	3/3	-2.8 (-2.9, -0.2)	1.1 (0.7, 2)	1.1 (0.7, 1.8)	-1.8 (-2.3, -1)	1.5 (-0.5, 2.1)
	↳ 2100		-2.4 (-5, -1)	1.7 (1.4, 2.6)	1.2 (1.2, 1.9)	-2.4 (-2.5, -2)	1.3 (-1, 4.4)
SSP5	**RCP1.9** in 2050	2/4	-1.5 (-3.9, 0.9)	6.7 (6.2, 7.2)	-1.9 (-3.5, -0.4)	3.1 (-0.1, 6.3)	-6.4 (-7.7, -5.1)
	↳ 2100		-0.5 (-4.2, 3.2)	7.6 (7.2, 8)	-3.4 (-6.2, -0.5)	4.7 (0.1, 9.4)	-8.5 (-10.7, -6.2)
	RCP2.6 in 2050	4/4	-3.4 (-6.9, 0.3)	4.8 (3.8, 5.1)	-2.1 (-4, 1)	3.9 (-0.1, 6.7)	-4.4 (-5, 0.2)
	↳ 2100		-4.3 (-8.4, 0.5)	9.1 (7.7, 9.2)	-3.3 (-6.5, -0.5)	3.9 (-0.1, 9.3)	-6.3 (-9.1, -1.4)
	RCP4.5 in 2050	4/4	-2.5 (-3.7, 0.2)	1.7 (0.6, 2.9)	0.6 (-3.3, 1.9)	-0.1 (-1.7, 6)	-1.2 (-2.6, 2.3)
	↳ 2100		-4.1 (-4.6, 0.7)	4.8 (2, 8)	-1 (-5.5, 1)	-0.2 (-1.4, 9.1)	-3 (-5.2, 2.1)
	Baseline in 2050	4/4	-0.6 (-3.8, 0.4)	0.8 (0, 2.1)	1.5 (-0.7, 3.3)	-1.9 (-3.4, 0.5)	-0.1 (-1.5, 2.9)
	↳ 2100		-0.2 (-2.4, 1.8)	1 (0.2, 2.3)	1 (-2, 2.5)	-2.1 (-3.4, 1.1)	-0.4 (-2.4, 2.8)

*Count of models included / Count of models attempted. One model did not provide land data and is excluded from all entries.

** One model could reach RCP1.9 with SSP4, but did not provide land data

Figure SPM.4: Pathways linking socioeconomic development, mitigation responses and land | Future scenarios provide a framework for understanding the implications of mitigation and socioeconomics on land. The Shared Socioeconomic Pathways (SSPs) span a range of different socioeconomic assumptions (Box SPM.1). They are combined with Representative Concentration Pathways (RCPs)[36] which imply different levels of mitigation. The changes in cropland, pasture, bioenergy cropland, forest, and natural land from 2010 are shown. For this Figure, Cropland includes all land in food, feed, and fodder crops, as well as other arable land (cultivated area). This category includes first generation non-forest bioenergy crops (e.g., corn for ethanol, sugar cane for ethanol, soybeans for biodiesel), but excludes second generation bioenergy crops. Pasture includes categories of pasture land, not only high-quality rangeland, and is based on FAO definition of 'permanent meadows and pastures'. Bioenergy cropland includes land dedicated to second generation energy crops (e.g., switchgrass, miscanthus, fast-growing wood species). Forest includes managed and unmanaged forest. Natural land includes other grassland, savannah, and shrubland. **Panel A:** This panel shows integrated assessment model (IAM)[37] results for SSP1, SSP2 and SSP5 at RCP1.9.[38] For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. For RCP1.9, SSP1, SSP2 and SSP5 results are from five, four and two IAMs respectively. **Panel B:** Land use and land cover change are indicated for various SSP-RCP combinations, showing multi-model median and range (min, max). (Box SPM.1) {1.3.2, 2.7.2, 6.1, 6.4.4, 7.4.2, 7.4.4, 7.4.5, 7.4.6, 7.4.7, 7.4.8, 7.5.3, 7.5.6, Cross-Chapter Box 1 in Chapter 1, Cross-Chapter Box 9 in Chapter 6}

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[36] Representative Concentration Pathways (RCPs) are scenarios that include timeseries of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover.

[37] Integrated Assessment Models (IAMs) integrate knowledge from two or more domains into a single framework. In this figure, IAMs are used to assess linkages between economic, social and technological development and the evolution of the climate system.

[38] The RCP1.9 pathways assessed in this report have a 66% chance of limiting warming to 1.5°C in 2100, but some of these pathways overshoot 1.5°C of warming during the 21st century by >0.1°C.

D. Action in the near-term

D.1 Actions can be taken in the near-term, based on existing knowledge, to address desertification, land degradation and food security while supporting longer-term responses that enable adaptation and mitigation to climate change. These include actions to build individual and institutional capacity, accelerate knowledge transfer, enhance technology transfer and deployment, enable financial mechanisms, implement early warning systems, undertake risk management and address gaps in implementation and upscaling (*high confidence*). {3.6.1, 3.6.2, 3.7.2, 4.8, 5.3.3, 5.5, 5.6.4, 5.7, 6.2, 6.4, 7.3, 7.4, 7.6, Cross-Chapter Box 10 in Chapter 7}

D.1.1 Near-term capacity-building, technology transfer and deployment, and enabling financial mechanisms can strengthen adaptation and mitigation in the land sector. Knowledge and technology transfer can help enhance the sustainable use of natural resources for food security under a changing climate (*medium confidence*). Raising awareness, capacity building and education about sustainable land management practices, agricultural extension and advisory services, and expansion of access to agricultural services to producers and land users can effectively address land degradation (*medium confidence*). {3.1, 5.7.4, 7.2, 7.3.4, 7.5.4}

D.1.2 Measuring and monitoring land use change including land degradation and desertification is supported by the expanded use of new information and communication technologies (cell phone based applications, cloud-based services, ground sensors, drone imagery), use of climate services, and remotely sensed land and climate information on land resources (*medium confidence*). Early warning systems for extreme weather and climate events are critical for protecting lives and property and enhancing disaster risk reduction and management (*high confidence*). Seasonal forecasts and early warning systems are critical for food security (famine) and biodiversity monitoring including pests and diseases and adaptive climate risk management (*high confidence*). There are high returns on investments in human and institutional capacities. These investments include access to observation and early warning systems, and other services derived from in-situ hydro-meteorological and remote sensing-based monitoring systems and data, field observation, inventory and survey, and expanded use of digital technologies (*high confidence*). {1.2, 3.6.2, 4.2.2, 4.2.4, 5.3.1, 5.3.6, 6.4, 7.3.4, 7.4.3, 7.5.4, 7.5.5, 7.6.4, Cross-Chapter Box 5 in Chapter 3}

D.1.3 Framing land management in terms of risk management, specific to land, can play an important role in adaptation through landscape approaches, biological control of outbreaks of pests and diseases, and improving risk sharing and transfer mechanisms (*high confidence*). Providing information on climate-related risk can improve the capacity of land managers and enable timely decision making (*high confidence*). {5.3.2, 5.3.5, 5.6.2, 5.6.3 5.6.5, 5.7.1, 5.7.2, 7.2.4, Cross-Chapter Box 6 in Chapter 5}

D.1.4 Sustainable land management can be improved by increasing the availability and accessibility of data and information relating to the effectiveness, co-benefits and risks of emerging response options and increasing the efficiency of land use (*high confidence*). Some response options (e.g., improved soil carbon management) have been implemented only at small-scale demonstration facilities and knowledge, financial, and institutional gaps and challenges exist with upscaling and the widespread deployment of these options (*medium confidence*). {4.8, 5.5.1, 5.5.2, 5.6.1, 5.6.5, 5.7.5, 6.2, 6.4}

D.2 Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits (*high confidence*). Co-benefits can contribute to poverty eradication and more resilient livelihoods for those who are vulnerable (*high confidence*). {3.4.2, 5.7, 7.5}

D.2.1 Near-term actions to promote sustainable land management will help reduce land and food-related vulnerabilities, and can create more resilient livelihoods, reduce land degradation and desertification, and loss of biodiversity (*high confidence*). There are synergies between sustainable land management, poverty eradication efforts, access to market, non-market mechanisms and the elimination of low-productivity practices. Maximising these synergies can lead to adaptation, mitigation, and development co-benefits through preserving ecosystem functions and services (*medium confidence*). {3.4.2, 3.6.3, Table 4.2, 4.7, 4.9, 4.10, 5.6, 5.7, 7.3, 7.4, 7.5, 7.6, Cross-Chapter Box 12 in Chapter 7}

D.2.2 Investments in land restoration can result in global benefits and in drylands can have benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services (*medium confidence*). Many sustainable land management technologies and practices are profitable within three to ten years (*medium confidence*). While they can require upfront investment, actions to ensure sustainable land management can improve crop yields and the economic value of pasture. Land restoration and rehabilitation measures improve livelihood systems and provide both short-term positive economic returns and longer-term benefits in terms of climate change adaptation and mitigation, biodiversity and enhanced ecosystem functions and services (*high confidence*). {3.6.1, 3.6.3, 4.8.1, 7.2.4, 7.2.3, 7.3.1, 7.4.6, Cross-Chapter Box 10 in Chapter 7}

D.2.3 Upfront investments in sustainable land management practices and technologies can range from about USD20 ha^{-1} to USD5000 ha^{-1}, with a median estimated to be around USD500 ha^{-1}. Government support and improved access to credit can help overcome barriers to adoption, especially those faced by poor smallholder farmers (*high confidence*). Near-term change to balanced diets (SPM B6.2.) can reduce the pressure on land and provide significant health co-benefits through improving nutrition (*medium confidence*). {3.6.3, 4.8, 5.3, 5.5, 5.6, 5.7, 6.4, 7.4.7, 7.5.5, Cross-Chapter Box 9 in Chapter 6}

D.3 Rapid reductions in anthropogenic GHG emissions across all sectors following ambitious mitigation pathways reduce negative impacts of climate change on land ecosystems and food systems (*medium confidence*). Delaying climate mitigation and adaptation responses across sectors would lead to increasingly negative impacts on land and reduce the prospect of sustainable development (*medium confidence*). (Box SPM.1, Figure SPM.2) {2.5, 2.7, 5.2, 6.2, 6.4, 7.2, 7.3.1, 7.4.7, 7.4.8, 7.5.6, Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}

D.3.1 Delayed action across sectors leads to an increasing need for widespread deployment of land-based adaptation and mitigation options and can result in a decreasing potential for the array of these options in most regions of the world and limit their current and future effectiveness (*high confidence*). Acting now may avert or reduce risks and losses, and generate benefits to society (*medium confidence*). Prompt action on climate mitigation and adaptation aligned with sustainable land management and sustainable development depending on the region could reduce the risk to millions of people from climate extremes, desertification, land degradation and food and livelihood insecurity (*high confidence*). {1.3.5, 3.4.2, 3.5.2, 4.1.6, 4.7.1, 4.7.2, 5.2.3, 5.3.1, 6.3, 6.5, 7.3.1}

D.3.2 In future scenarios, deferral of GHG emissions reductions implies trade-offs leading to significantly higher costs and risks associated with rising temperatures (*medium confidence*). The potential for some response options, such as increasing soil organic carbon, decreases as climate change intensifies, as soils have reduced capacity to act as sinks for carbon sequestration at higher temperatures (*high confidence*). Delays in avoiding or reducing land degradation and promoting positive ecosystem restoration risk long-term impacts including rapid declines in productivity of agriculture and rangelands, permafrost degradation and difficulties in peatland rewetting (*medium confidence*). {1.3.1, 3.6.2, 4.8, 4.9, 4.9.1, 5.5.2, 6.3, 6.4, 7.2, 7.3; Cross-Chapter Box 10 in Chapter 7}

D.3.3 Deferral of GHG emissions reductions from all sectors implies trade-offs including irreversible loss in land ecosystem functions and services required for food, health, habitable settlements and production, leading to increasingly significant economic impacts on many countries in many regions of the world (*high confidence*). Delaying action as is assumed in high emissions scenarios could result in some irreversible impacts on some ecosystems, which in the longer-term has the potential to lead to substantial additional GHG emissions from ecosystems that would accelerate global warming (*medium confidence*). {1.3.1, 2.5.3, 2.7, 3.6.2, 4.9, 4.10.1, 5.4.2.4, 6.3, 6.4, 7.2, 7.3, Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}