CLIMATE ANALYTICS

Overview briefing on the IPCC Special Report on Climate Change and Land

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AUTHORS
Carl-Friedrich Schleussner
Alexandrine Lanson
Susanne Baur
Claire Fyson
Thessa Beck
Corinne Kowalski
Alexander Nauels

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Table of Contents

Executive summary

Land is under growing human pressure at 1°C of warming to date

The IPCC special report on climate change and land (full name "Special Report on climate change, desertification, ⇒land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems") outlines how land is subject to human pressure in the Anthropocene. A quarter of land is already considered degraded, nearly three quarters of it is exploited or occupied (agriculture, pasture, forestry, etc.) and two thirds of the forests are managed (e.g., timber extraction or recreational uses), leaving less than a quarter of this land free of direct human influence.

At about 1°C of global warming, widespread impacts are already affecting land. The frequency, intensity and duration of many ⇒extreme events have increased in many parts of the world, especially heat waves, droughts and heavy precipitation events. The impacts of these effects are already seen through land and terrestrial ecosystems degradation, ⇒desertification and increasing food insecurity. Desertification hotspots extended to about 9% of drylands, affecting about 500 (±120) million people in 2015. 500 million people would equate to the inhabitants of Brazil and the US combined.

Land based emissions contribute about a quarter to the ongoing climate change

While industrial activities remain the dominant factor in the increase of greenhouse gases in the atmosphere, all land-use activities, particularly deforestation and agricultural activities, contribute to about a quarter of these emissions (over the 2007-2016 period).

In total, between 21-37% of global greenhouse emissions are attributable to the food system, a significant part of which is wasted. Global food loss and waste amount to 25-30% of total food produced and equaled 8-10% of total anthropogenic GHG emissions during 2010-2016. Without interventions these are projected to increase significantly.

Climate impacts on land accelerate at an alarming pace above 1.5°C

Widespread climate risks and impacts increase at an alarming pace above 1.5°C. Risks for permafrost degradation are already *high* at 1.5°C and assessed *very high* if warming exceeds 2°C, indicating great risks of irreversible losses. Risks for wildfire damage are assessed *high* above 1.5°C and the chances of experiencing *high* risks for vegetation loss, dryland water scarcity and tropical crop yield decline increase rapidly above 1.5°C. Risks for food system instabilities with periodic food shocks across regions are high already at 1.5°C with rapidly increasing chances of *very high* risks of sustained global food supply disruptions above 1.5°C. More than 1 billion people (3 times the US population) could be exposed to various impacts related to water, energy and land sectors under a 2°C warming by mid-century, of which more than 200 million would be highly vulnerable to its impacts. Food insecurity is a critical ‘push’ factor driving international migration.

Future climate impacts strongly depend on different socio-economic drivers of development poverty eradication, international cooperation and sustainability concerns. A scenario that resembles most closely the globally inclusive, solidaric and sustainable approach required to achieve the SDGs (the so-called SSP1 scenario) will help to avoid the most severe impacts on land systems and vulnerable populations, while in a world of regional rivalry, these will be strongly exacerbated.

Land has a crucial role to play in climate mitigation

Key land based measures are required to achieve the goals of the Paris Agreement and there is a huge potential for behavioural shifts identified, too. Reduced deforestation and forest degradation could save 0.4-5.8 GtCO2-eq yr^{-1}, a shift towards plant-based diets 0.7-8.0 GtCO2-eq yr^{-1} and reduced food and agricultural waste 0.8-4.5 GtCO2-eq yr^{-1}. For comparison purposes; in 2010 the whole transport sector produced 7.0 GtCO2-eq of direct GHG emissions.

A broad range of response options based on land management have been identified that have multiple co-benefits across the dimensions of mitigation, adaptation and desertification, land degradation and food security. However, the efficacy of many of these options – often referred to as 'nature based solutions' – will be limited under higher levels of warming, meaning that they must be accompanied by rapid emissions reductions in other sectors consistent with limiting warming to 1.5°C.

A contribution of land-based options for ⇒carbon dioxide removal such as biochar addition to soil, ⇒reforestation, ⇒afforestation, agroforestry, soil carbon management and ⇒bioenergy with carbon capture and storage (BECCS) is required in Paris-compatible mitigation pathways. Sustainable best practice applications for all these options have been identified that should be the focus of their deployment. Large-scale deployment of land-based mitigation options beyond sustainability limits could have substantial negative side-effects on a sustainable land future including food security and biodiversity conservation. Furthermore, accumulated carbon in many land-based sinks (⇒see carbon sink) is vulnerable to future climate change impacts. It is thus of paramount importance to limit the future reliance on ⇒carbon dioxide removal through stringent near-term emission reductions.

Urgent near-term mitigation action is key

Widespread land-based impacts of climate change are evident today and will become ever more severe over the coming decades. On the current emissions trajectory, a warming of 1.5°C would be exceeded before mid-century, with respective high and potential very high impacts across a whole range of identified land-based risks. Stringent near-term mitigation to slow the rate of warming in the coming decades, to achieve ⇒net-zero CO_2 emissions by mid-century and to limit global temperature increase to 1.5°C is therefore key to avoid the ever accelerating impacts of climate change on land. The longer action is delayed, the more we risk crossing points of no return, such as irreversible land degradation in some regions, and the more the implementation of solutions will become less effective, such as for ⇒carbon sequestration in soils.

Furthermore, stringent near-term emission reductions are key to reduce an undue reliance on potentially unsustainable large-scale ⇒carbon dioxide removal. At the same time, questions of carbon dioxide removal raise fundamental concerns of equity and fairness. Literature published beyond the IPCC special report outlines, how applying equity principles clearly outlines the responsibility of historic emitters for carbon dioxide removal. For historical big emitters such as the US, China or the EU, failing to reduce emission levels in 2030 to 1.5°C compatible levels, generates about 20–70 additional gigatons of CDR responsibility over this century per tonne of excess emissions in 2030.

Table ES 1: Summary of key climate impacts and risks at 1.5°C vs. 2°C identified in the report.

Projected impacts and risks	1.5°C	2°C
Arctic permafrost thawing	21-37%	35-47%
People exposed and vulnerable to crop yield change under SSP3	20 million	178 million

World population exposed to new forms of or aggravated water scarcity, compared to 2000	Additional 4%	Additional 8%
Dryland population exposed and vulnerable to water stress in SSP1, 2050 population	2%	3%
Dryland population exposed and vulnerable to water stress in SSP3, 2050 population	20%	22%
People exposed to habitat degradation in non-dryland regions under SSP1 (temperature reached)	Less than 100 million	257 million
People exposed to habitat degradation in non-dryland regions under SSP3 (temperature reached)	107 million	1156 million
Dryland population vulnerable to water stress, drought intensity and habitat degradation in 2050 under SSP2	178 million	220 million

Arrows (⇒) in the text in front of words indicate that a definition of the term is given in the Glossary at the end of the report.

1. Land and climate in a warming world

1.1. Land use impacts and their contribution to climate change

1.1.1 Terrestrial greenhouse gas fluxes on unmanaged and managed lands

- Land is simultaneously a source and ⇒sink for several greenhouse gases; in terms of CO_2, it provided a global net removal of -6.0 ± 3.7 $GtCO_2\ yr^{-1}$ from 2007 to 2016;
- Agriculture, Forestry and Other Land Use (AFOLU) represents 23% of total net anthropogenic emissions of GHGs from human activities globally during 2007-2016, resulting in net emissions of 12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$. In terms of CO_2 equivalents, just under half of these emissions are CO_2 emissions from Forestry and Other Land Use (FOLU) (5.2 ± 2.6 $GtCO_2\ yr^{-1}$); the remainder are non-CO_2 emissions, mostly from agriculture (5.6 ± 2.8 $GtCO_2eq\ yr^{-1}$ of CH_4, and 0.5 ± 0.3 $GtCO_2eq\ yr^{-1}$ of N_2O)
- Non-anthropogenic processes on managed and unmanaged lands removed 11.2 ± 2.6 $GtCO_2\ yr^{-1}$ during the same period.

Land is simultaneously a source and sink for several greenhouse gases (GHGs) (mostly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)); both natural and anthropogenic processes determine fluxes of GHGs. The total net land-atmosphere flux of CO_2 on both managed and unmanaged lands *very likely* provided a global net removal of CO_2 from the atmosphere from 2007 to 2016 (-6.0 ± 3.7 $GtCO_2\ yr^{-1}$) (see Figure 1). This net removal is comprised of two major components: (i) modelled net anthropogenic CO_2 emissions from FOLU (5.2 ± 2.6 $GtCO_2\ yr^{-1}$), driven by land cover change, including deforestation and ⇒afforestation/⇒reforestation, and wood harvesting, and (ii) modelled net removals due to non-anthropogenic processes (11.2 ± 2.6 $GtCO_2\ yr^{-1}$) on managed and unmanaged lands, driven by environmental changes such as increasing CO_2, nitrogen deposition and changes in climate.

AFOLU is a significant net source of GHG emissions: it has been assessed with *medium confidence* to represent 23% (12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$) of total net anthropogenic emissions of GHGs from human activities globally during 2007-2016 (13% of total CO_2, 44% of total CH_4, and 81% of total N_2O emissions). Moreover, there is *high confidence* that the gross emissions of CO_2 from AFOLU (33% of total global emissions) are indicative of the mitigation potential of reduced deforestation. There is *medium confidence* that 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 regrowth following wood harvest and agricultural abandonment (see Figure 1).

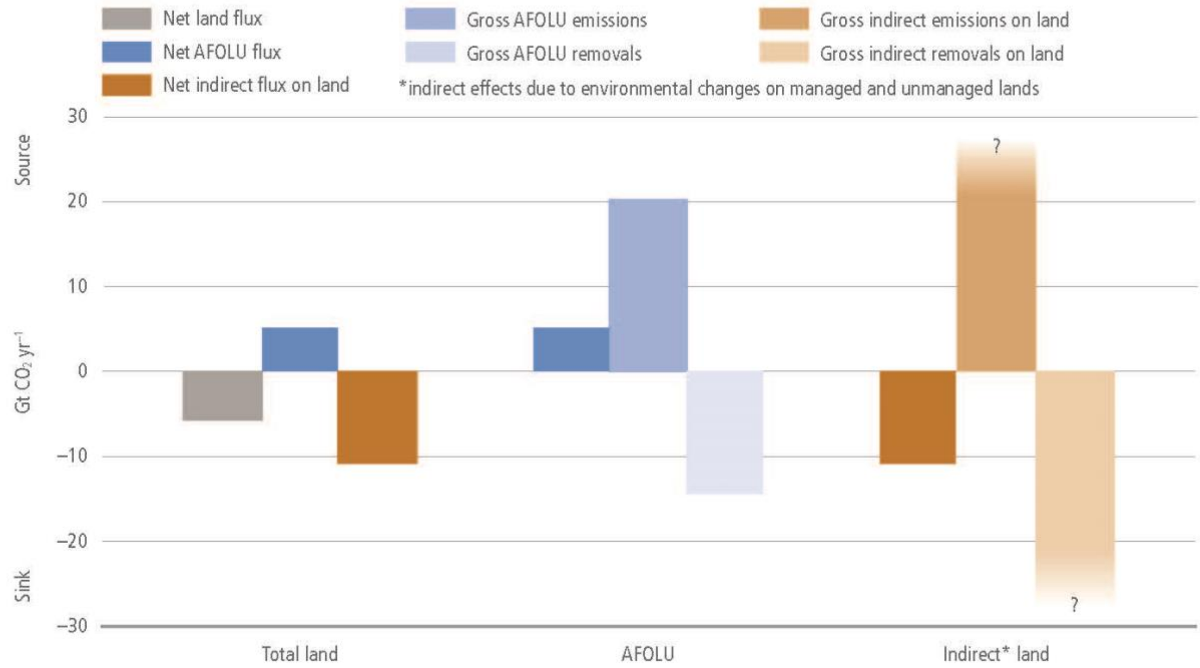

*Figure 1: **Net and gross fluxes of CO_2 from land (annual averages for 2008–2017)**.Left: The total net flux of CO_2 between land and atmosphere (grey) is shown with its two component fluxes, (i) net AFOLU emissions (blue), and (ii) the net land sink (brown), due to indirect environmental effects and 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.*

1.1.2 Greenhouse gas emissions from food systems

- About 21-37% of total GHG emissions are attributable to the food system;
- Global food loss and waste amount to 25-30% of total food produced and equaled 8-10% of total anthropogenic GHG emissions during 2010-2016.

About 21-37% of total GHG emissions are attributable to the food system. These are from agriculture and land use, storage, transport, packaging, processing, retail, and consumption. There is high confidence that 9-14% of total GHG emissions are from crop activities (CH4 emissions from rice, CO2 emissions from peatland cultivation, N2O emissions from fertilizer applications) and livestock activities (including non-CO2 gases from enteric fermentation from ruminant animals and from anaerobic fermentation in manure management processes, as well as non-CO2 gases from manure deposited on pastures) within the farm gate. 5-14% of emissions are from land use and land-use change including deforestation and peatland degradation. There is *medium confidence* that 5-10% of emissions are from supply chain activities. These estimates include GHG emissions from food loss and waste (25-30% of total food produced), which made up 8-10% of total anthropogenic GHG emissions during 2010-2016.

During the period 2007-2016, total GHG emissions from agriculture reached 6.2 ± 1.4 GtCO2-eq yr^{-1} and when including relevant land use emissions they further increase to 11.1 ± 2.9 GtCO2-eq yr^{-1}. Asia, especially India, China and Indonesia accounted for roughly 50% of global emissions from croplands over the period 2010-2016. Without intervention, there is *high confidence* that they will increase by about 30–40% by 2050, due to increasing demand based on population and income growth and dietary change.

1.1.3 Biophysical and biogeochemical land forcing and feedbacks to the climate system

- The contribution of anthropogenic land cover changes to the net global warming throughout the 20th century has been assessed at 0.078 ± 0.093°C;
- ⇒Short-lived climate forcers such as mineral dust of black carbon strongly affect regional climate, through warming and cooling effects;
- Changes in land conditions modulate the likelihood, intensity and duration of many ⇒extreme events including heatwaves and heavy precipitation events.

Changes in land conditions from human use or climate change affect regional and global climate. On the global scale, there is *very high confidence* that this is driven by changes in emissions or removals of CO2, CH4 and N2O by land (biogeochemical effects) and by changes in the surface ⇒albedo (for example due to ⇒desertification or permafrost thaw). There is *high confidence* that any local land changes that redistribute energy and water vapour between the land and the atmosphere influence regional climate (biophysical effects).

Temperature

The simulated net change in mean global annual surface air temperature (accounting simultaneously for biogeochemical (warming, *very high confidence*) and biophysical (cooling, *medium confidence*) effects of land on climate), averaged over all the simulations, is a warming of 0.078 ± 0.093°C (models do not agree on the sign of the contribution). The impact of these effects therefore remains uncertain. In the future, the effect of land cover changes on global temperature is projected to differ between regions: by 2050, and following the SRES B2 scenario[1], the contribution of land cover changes to the total temperature change can be as large as 15% in many boreal regions, and as large as 40% in south-western tropical Africa.

Short-lived climate forcers

There is *medium confidence* that regional climate is strongly affected by ⇒short-lived climate forcers (e.g., mineral dust, carbonaceous aerosols, biogenic volatile organic compounds (BVOCs)).

Mineral dust can absorb or scatter shortwave and longwave radiation and affects cloud formation and development, thus potentially influencing precipitation patterns and amounts. There is *low confidence* that dust emissions have increased by 25% from the preindustrial period to the present day, because of climate change (50%) and land user cover change (40%) such as conversion of natural land to agriculture, and that these emissions have a slight cooling effect. There is *no agreement* about the direction of future changes in dust emissions.

The main sources of carbonaceous aerosols (e.g., organic carbon (OC), black carbon (BC), brown carbon (BrC)) are burning of fossil fuels, biomass-burning emissions and secondary organic aerosols from natural BVOC emissions. While OC is reflective and scatters solar radiation, it has a cooling effect on climate, whereas BC and BrC absorb solar radiation and have a warming effect on the climate system. Deposition of aerosols, especially BC, on snow and ice surfaces can reduce ⇒albedo and increase

[1] Special Report on Emissions Scenario; the B2 scenario consists in a continuously increasing population, an emphasis on local rather than global solutions to economic, social and environmental stability, an intermediate level of economic development and slow and fragmented technological change.

warming as a self-reinforcing feedback. Uncertainties in the balance of cooling and warming effects remain high.

BVOCs are emitted in large amounts by forests; their emissions represent a carbon loss from the ecosystem, which can be up to 10% of the carbon fixed by photosynthesis under stressful conditions. A further 2°C-3°C rise in global mean temperature could increase global BVOC emissions by an additional 30-45%, resulting in a cooling effect. On the other hand, the decrease in BVOC emissions from the historical conversion of forests to cropland is found with *low confidence* to have resulted in a positive radiative forcing through aerosol effects. Future deforestation according to the land use scenario in RCP8.5 leads to a 4% decrease in BVOC emissions at the end of the century, resulting in a warming effect.

Extreme events

There is high confidence that changes in land conditions modulate the likelihood, intensity and duration of many ⇒extreme events including heatwaves, and *medium confidence* they do so for heavy precipitation events. 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. There is *high confidence* that both global warming and urbanisation can enhance warming in cities and their surroundings (heat island effect), especially during heat related events, including heat waves, and *medium confidence* that urbanisation increases extreme rainfall events over or downwind of cities.

1.2. Impacts of climate change on land

1.2.1 Observed impacts at 1°C of warming

- Mean land surface air temperature has increased faster than global mean surface temperature;
- The frequency and intensity of some ⇒extreme weather and climate events have increased as a consequence of global warming;
- Climate change exacerbates the rate and magnitude of several ongoing ⇒land degradation processes and introduces new changes in vegetation cover and distribution or coastal erosion.

Temperature

There is *high confidence* 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) (see Figure 2): mean land surface air temperature increased by 1.53°C while global mean surface temperature increased by 0.87°C.

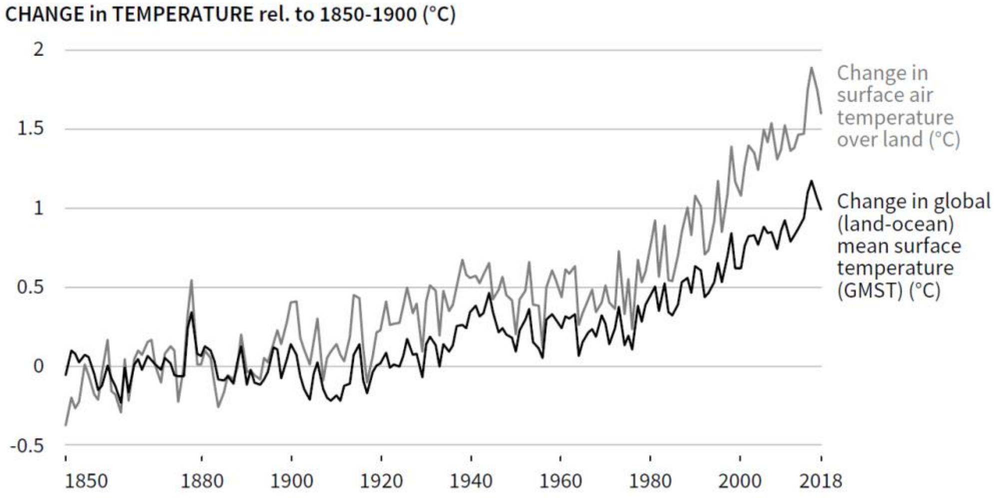

Figure 2: (fig SPM.1a) Observed temperature change relative to 1850-1900. Since the pre-industrial period (1850-1900), the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST).

Extreme events

The frequency and intensity of some ⇒extreme weather and climate events have increased as a consequence of global warming; recent heat-related events, for example, heatwaves, have been made more frequent or intense due to anthropogenic GHG emissions in most land regions. It is assessed with *medium confidence* that frequency and intensity of droughts in Amazonia, north-eastern Brazil, Patagonia, most of Africa, and north-eastern China have increased.

Desertification

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 causing ⇒desertification in some dryland areas, in interaction with human activities. 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. There is *high confidence* that desertification has already reduced agricultural productivity and incomes, and *medium confidence* that it contributed to the loss of biodiversity in some dryland regions.

Land degradation

The number of people whose livelihood depends on ⇒degraded lands has been estimated with *very low confidence* to be about 1.5 billion worldwide. There is *high confidence* that 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. Land degradation reduces land productivity and increases the workload of managing the land, affecting women disproportionally in some regions. Climate change is assessed with *high confidence* to exacerbate the rate and magnitude of several ongoing land degradation processes and introduces new degradation patterns, such as vegetation cover and distribution or coastal erosion. Human-induced global warming has already caused observed changes in two drivers of land degradation: increased frequency, intensity and/or amount of heavy precipitation and increased heat stress. There is *very high confidence* that land degradation and climate change act as threat multipliers for already precarious livelihoods, leaving them highly sensitive to ⇒extreme climatic events, with consequences such as poverty and food insecurity and, in some cases, migration, conflict and loss of cultural heritage.

1.2.2 Risks for terrestrial systems at different levels of warming

- ⇒Extreme events are projected to increase in frequency and intensity; - ⇒Desertification and ⇒land degradation processes are projected to accelerate under climate change; - These changes will increase biodiversity loss and cause reductions in crop and livestock productivity, threatening food security.

Extreme events

Heatwaves are projected with *high confidence* to increase in frequency, intensity and duration in most parts of the world, and drought frequency and intensity are projected with *medium confidence* to increase in some regions that are already drought prone, predominantly in the Mediterranean, central Europe, the southern Amazon and southern Africa. There is *high confidence* that these changes will impact ecosystems, food security and land processes including GHG fluxes.

Desertification

Risks from desertification are projected to increase due to climate change with *high confidence*. Under shared socio-economic pathway SSP2[1] ('Middle of the Road') at 1.5°C, 2°C and 3°C of global warming in 2050, 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. Under SSP1 ('Sustainability'), global warming of 2°C is projected to leave 974 million exposed, and 35 million vulnerable, while under SSP3 ('Fragmented World'), the same level of warming is projected to leave 1267 million exposed and 522 million vulnerable. Around half of the vulnerable population is in South Asia, followed by Central Asia, West Africa and East Asia.

There is *medium confidence* that climate change will exacerbate several desertification processes. Although the ⇒CO2 fertilisation effect is enhancing vegetation productivity in drylands, decreases in water availability have a larger effect than CO2 fertilisation in many dryland areas. Aridity, the area at risk of salinisation and the potential for water driven soil erosion in many dryland areas are projected to increase, the latter leading to soil organic carbon decline in some dryland areas. There is *high confidence* that the provision of dryland ecosystem services and lower ecosystem health will be reduced, including losses in biodiversity. Desertification and changing climate are projected to cause reductions in crop and livestock productivity (*high confidence)*, and to modify the composition of plant species and reduce biological diversity across drylands (*medium confidence)*. Rising CO2 levels will favour more rapid expansion of some invasive plant species in some regions. There is *medium confidence* that projected increases in temperature and the severity of drought events across some dryland areas can increase chances of wildfire occurrence.

[1] Cf Technical note

Land degradation

There is *medium confidence* that global warming beyond present day will further exacerbate ongoing ⇒land degradation processes through increasing floods, drought frequency and severity, intensified cyclones, and *very high confidence* it will do so through sea level rise, with outcomes being modulated by land management. There is *high confidence* that erosion of coastal areas because of sea level rise will increase worldwide, and *very high confidence* that 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.

Biodiversity

There is *medium confidence* that land use caused global biodiversity to decrease by around 11-14% since 1961. Further losses are projected with increasing desertification, land degradation and climate change. The concomitance of land-use and climate change pressures renders ecosystem restoration a key challenge.

1.2.3 Impacts on the land carbon sink

- The land ⇒carbon sink has increased since 1900, absorbing 29% of global anthropogenic emissions of CO2 during 2008–2017;
- Nevertheless, it is at risk of reversal due to several climate change impacts.

There is *robust evidence* that the land sink is driven largely by the indirect effects of environmental change (e.g., climate change, increased atmospheric CO2 concentration, nitrogen deposition) on unmanaged and managed lands. It has generally increased since 1900, absorbing 29% of global anthropogenic emissions of CO2 (11.7 ± 3.7 GtCO2 yr^{-1}) during 2008-2017, and is assessed with *medium confidence* to have slowed the rise in global land-surface air temperature by 0.09 ± 0.02°C since 1982.

However, the future of the land sink is uncertain. There is *high confidence* that nutrient (e.g., nitrogen, phosphorus) availability can limit future plant growth and carbon storage under rising CO2. There is *low confidence* that increased emissions from vegetation and soils due to climate change in the future will counteract potential sinks that are due to ⇒CO2 fertilisation. Soils are a finite carbon sink and ⇒sequestration rates may decline to negligible levels over as little as a couple of decades as soils reach carbon saturation. The soil carbon sink is at risk of reversal, in particular due to increased soil respiration under higher temperatures. Moreover, there is *medium confidence* that thawing of high latitude/altitude permafrost will increase rates of soil organic carbon loss and change the balance between CO2 and CH4 emissions (the total soil organic carbon storage in permafrost amounts about 1500 ± 200 PgC). Nevertheless, there is *limited evidence* that substantial net carbon release of the coupled vegetation-permafrost system will probably not occur before about 2100 because carbon uptake by increased vegetation growth will initially compensate for GHG releases from permafrost. 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.

1.2.4 Avoidable risks by limiting warming to 1.5°C

- Risks for natural and human systems are projected to severely increase with temperatures; - Limiting warming to 1.5°C can limit these risks and avoid ⇒tipping points such as the permafrost one.

As previously explained, there is *high confidence* that current global warming (around 0.87°C for the global average) is associated with moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation and tropical crop yield decline. These 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 with *medium confidence* to be high. At around 2°C, there is *medium confidence* that risks from permafrost degradation and food supply instabilities are projected to reach very high levels. For example, while approximately, 21–37% of Arctic permafrost is projected to thaw under a 1.5°C of warming, this increases to 35–47% of the Arctic permafrost thawing under 2°C. If climate stabilised at 2°C, still approximately 40% of permafrost area would be lost, leading to nearly four million people and 70% of current infrastructure in the pan-Arctic permafrost area exposed to permafrost thaw and high hazard. Still at 2°C, an additional 8% of the world population (of population in 2000, compared to 1.5°C) will be exposed to new forms of aggravated water scarcity.

Between 2°C and 3°C a collapse of permafrost may occur with a drastic biome shift from tundra to boreal forest, and potentially mean the cross of a ⇒tipping point, leading to enhanced greenhouse gases emission. At around 3°C, there is *medium confidence* that risks from vegetation loss, wildfire damage, and dryland water scarcity will also reach very high levels. For this intense dryland water scarcity, the only adaptation option would be the migration from these regions.

This risk evolution with temperature is depicted in Figure 3 (section 1.3.4).

1.3. Food security

There is *high confidence* that climate change already affects, and is projected to affect, the four pillars of food security and their interactions: availability (e.g. reduced yield in crop and livestock systems or reduced food quality affecting availability), access (e.g. yield reductions, or price rise and spike effects on low-income consumers), utilisation (e.g. impacts on food safety due to increased prevalence of microorganisms and toxins) and stability (e.g. greater instability of supply due to increased frequency and severity of ⇒extreme events).

These impacts of climate change on food systems can lead to increasing undernourishment, increasing obesity and ill health (driven by limited availability of affordable nutritious foods), increasing environmental degradation and GHG emissions associated with food production, and increasing food insecurity due to competition for land and natural resources (e.g., for land-based mitigation).

1.3.1. *Observed impacts of climate change on food systems at 1°C*

- Climate change has decreased global mean yields between 1981 and 2010 of maize, wheat, and soybeans by 4.1, 1.8 and 4.5%, respectively, relative to preindustrial climate;
- Smallholder farmers are considered to be disproportionately vulnerable to climate change.

Crop production

There is *high confidence* that observed climate change is already affecting crop production through increasing temperatures, changing precipitation patterns, and greater frequency of some ⇒extreme events. These impacts are negative in many lower-latitude regions and positive in many higher-latitude regions. Climate change has decreased global mean yields between 1981 and 2010 of maize, wheat, and soybeans by 4.1, 1.8 and 4.5%, respectively, relative to the preindustrial climate. For example, Australia, India, Africa and Italy have experienced yield declines, reaching 27% in Australia from 1991 to 2015, and widening food security gaps have been experienced in regions such as the Sahel and the Himalayas. In Argentina there has been an increase in yield variability of maize and soybeans, and farmers are already adjusting their planting and soil management strategies in some parts of South America.

Pastoralism

Pastoralism is practiced in more than 75% of countries by between 200 and 500 million people. There is *high confidence* that observed impacts in pastoral systems include decreasing rangelands, decreasing mobility, decreasing livestock numbers, poor animal health, overgrazing, ⇒land degradation, decreasing productivity, decreasing access to water and feed, and increasing conflicts for the access to pasture land. For instance, in Mongolia, grassland productivity has declined by 20–30% over the latter half of the 20th century, and ewe average weight reduced by 4 kg on an annual basis, or about 8% since 1980.

Smallholder farmers

Across the world, smallholder farmers are considered to be disproportionately vulnerable to climate change because changes in temperature, rainfall and the frequency or intensity of extreme weather events directly affect their crop and animal productivity as well as their household food security, income and well-being. In rural Mexico, years with a high occurrence of heat lead to a reduction in local employment by up to 1.4% in a medium emissions scenario, particularly for wage work and non-farm labour, with impacts on food access.

1.3.2. *Projected impacts on food systems at different levels of warming*

- Climate change is projected to cause global reductions in crop and livestock productivity, with risks to food systems becoming increasingly severe with increasing temperatures;
- Models project that 1-183 million additional people will be at risk of hunger as a result of climate change

Food systems, and therefore food security, will be increasingly affected by projected future climate change. There is *high confidence* that 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 scenario without climate change. There is *high confidence* that given increasing ⇒extreme events and food system interconnectedness, risks of food system disruptions are growing.

Crop

The projected global mean yields of maize and soybean at the end of this century decrease with warming, whereas those of rice and wheat increase with warming but level off at about 3°C (2091-2100 relative to 1850-1900). Areas suitable for growing coffee are expected to decrease by 21% in Ethiopia with global warming of 2.4°C and more than 90% in Nicaragua with 2.2°C local temperature increase. There is *high confidence* that 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. Vegetables growing in higher baseline temperatures (>20°C) experience the strongest yield reductions, with projected declines of 31.5% at 4°C warming. In Africa, 30–60% of the common bean growing area and 20–40% of the banana growing areas are projected to lose viability with a global temperature increase of 2.6°C and 4°C, respectively.
While increased CO2 is projected to be beneficial for crop productivity at lower temperature increases, there is *high confidence* it will lower nutritional quality (e.g., wheat grown at 546–586 ppm CO2 has 5.9–12.7% less protein, 3.7–6.5% less zinc, and 5.2–7.5% less iron). Furthermore, there is *high confidence* that distributions of pests and diseases will change, as well as pollinators, affecting production negatively in many regions.

Livestock

Projected impacts on grazing systems include changes in herbage growth (due to changes in atmospheric CO2 concentrations, rainfall, and temperature regimes) and changes in the composition of pastures and in herbage quality, as well as direct impacts on livestock. For the net primary production in rangelands, significant regional heterogeneity in responses are projected, with large increases in annual productivity in northern regions (e.g., a 21% increase in productivity in the USA and Canada) and large declines in western Africa (-46% in Sub-Saharan western Africa) and Australia (–17%). Rangeland composition is also projected to change.

Direct and indirect effects on livestock are linked to increased water and temperature stress (affecting feed intake and fertility), potentially leading to animal morbidity, mortality and distress sales, but are also related to the impacts on the feed base, whether pastures or crops, leading to increased variability and sometimes reductions in availability and quality of the feed for the animals. In Kenya, some 1.8 million extra cattle could be lost by 2030 because of increased drought frequency, the value of lost animals and production foregone amounting to 630 million US$.

1.3.3. Associated risks for human systems: food price hikes and spikes, conflict risk and migration

- Food insecurity is a critical ‘push’ factor driving international migration, along with conflict, income inequality, and population growth;
- Migration and conflicts have already occurred (e.g., 300,000 rural Syrians farm families displaced between 2007 and 2010 following a severe drought).

Under SSP2, the dryland population vulnerable to water stress, drought intensity and habitat degradation is projected with *low confidence* 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.

Food price hikes and spikes

Through impacts on food prices, poor people's food security is particularly threatened. Across SSPs 1, 2, and 3, global crop and economic models project a 1–29% cereal price increase in 2050 due to climate change (RCP 6.0, which reaches around 1.8°C of warming in 2050), which would impact consumers globally through higher food prices; there is *high confidence* that regional effects will vary. Decreased yields can impact nutrient intake of the poor by decreasing supplies of highly nutritious crops and by promoting adaptive behaviours that may substitute crops that are resilient but less nutritious. In Guatemala, food prices and poverty have been correlated with lower micronutrient intakes. There is *high confidence* that vulnerable urban areas are particularly affected, where livelihood impacts are particularly severe for the individuals and groups that have scarce resources or are socially isolated. These people often lack power and access to resources, adequate urban services and functioning infrastructure. As climate events become more frequent and intense, this can increase the scale and depth of urban poverty. Urban floods and droughts may result in water contamination increasing the incidence of diarrhoeal illness in poor children. In the developed world, poverty is more typically associated with calorically-dense but nutrient-poor diets, obesity, overweight, and other related diseases.

Given the potential for shocks driven by changing patterns of ⇒extreme weather to increase with climate change (for example, by mid-century, over 80% of summers are projected to have average temperatures that are likely to exceed the hottest summer in the ⇒Dust Bowl years, leading to yield losses that are about 50% larger than the severe drought of 2012), there is the potential for market volatility to disrupt food supply through creating food price spikes. This potential is exacerbated by the interconnectedness of the food system with other sectors (i.e., food system dependency on water, energy, and transport), so the impact of shocks can propagate across sectors and geographies.

Conflict

Increased resource competition can aggravate the potential for migration to lead to conflict. When populations continue to increase, competition for resources will also increase, and resources will become even scarcer due to climate change. In agriculture-dependent communities in low-income contexts, droughts have been found to increase the likelihood of violence and prolonged conflict at the local level, which eventually pose a threat to societal stability and peace. In contrast, conflicts can also have diverging effects on agriculture due to land abandonment, resulting in forest growth, or agriculture expansion causing deforestation, for example, in Colombia.

Many conflicts have already occurred. Persistent drought in Morocco during the early 1980s resulted in food riots and contributed to an economic collapse. A drought in Somalia fuelled conflict through livestock price changes, establishing livestock markets as the primary channel of impact. Cattle raiding as a normal means of restocking during drought in the Great Horn of Africa led to conflict whereas a region-wide drought in northern Mali in 2012 wiped out thousands of livestock and devastated the livelihoods of pastoralists, in turn swelling the ranks of armed rebel factions and forcing others to steal and loot for survival.

Inter-annual adjustments in international trade can play an important role in shifting supplies from food surplus regions to regions facing food deficits which emerge as a consequence of extreme weather events, civil strife, and/or other disruptions.

Migration

Food insecurity is a critical 'push' factor driving international migration, along with conflict, income inequality, and population growth. The act of migration itself causes food insecurity, given the lack of income opportunities and adverse conditions compounded by conflict situations. In Africa, persistent droughts and ⇒land degradation contributed to both seasonal and permanent migration, worsening the vulnerability of different households. In rural Ecuador, adverse environmental conditions prompt out-migration, although households respond to these challenges in diverse ways resulting in complex migratory responses. In Syria the severe drought triggered agricultural collapse and displacement of rural farm families, with approximately 300,000 families going to Damascus, Aleppo and other cities between 2007 and 2010.

For coastal communities, recurrences of natural disasters and crises threaten food security through impacts on traditional agriculture, causing their forced migration and displacement to highlands in search of better living conditions. Although considerable differences occur in the physical manifestations of severe storms, such climate stressors threaten the life-support systems of many atoll communities. The failure of these systems resulting from climate disasters propel vulnerable atoll communities into poverty traps, and low adaptive capacity could eventually force these communities to migrate. Food security in the Pacific, especially in Micronesia, has worsened in the past half century and climate change is *likely* to further hamper local food production, especially in low-lying atolls. On Yap Island, ⇒extreme weather events are affecting every aspect of atoll communities' existence, mainly due to the islands' small size, their low elevation, and extensive coastal areas. In many atoll nations in the Western Pacific, migration has increasingly become a sustainable livelihood strategy, irrespective of climate change. In Lamen Bay, Vanuatu, migration is both a cause and consequence of local vulnerabilities. Indeed, while migration provides an opportunity for households to meet their immediate economic needs, it limits the ability of the community to foster longer-term economic development. At the same time, migration adversely affects the ability of the community to maintain food security due to lost labour and changing attitudes towards traditional ways of life among community members.

1.3.4. Risks under different socio-economic development pathways

Risks of ⇒desertification, ⇒land degradation and food security are much lower under SSP1 (moderate risks under a <2°C scenario) than under SSP3 (transition from high to very high risk at around 2°C of warming).

Figure 3 shows the risks to humans and ecosystems from changes in land-based processes as a result of climate change (Panel A), but also the difference between SSP1 and SSP3 in terms of climate related risks (Panel B). It highlights the much higher risks under SSP3 and under higher levels of warming: risks related to water scarcity in drylands, to habitat degradation, wildfire and floods, and to food security remain moderate for SSP1 under a <2°C scenario, whereas in SSP3 the transition from moderate to high risk occurs between 1.2°C and 1.7°C. Under SSP3, there is *medium confidence* that food security is at very high risk under a 2.5°C scenario, and that, regardless of the SSP, food supply instabilities are already at high risk (periodic food shocks across regions) for a 1.3°C warming and at very high risk for a 2°C warming, which corresponds to sustained food supply disruptions globally.

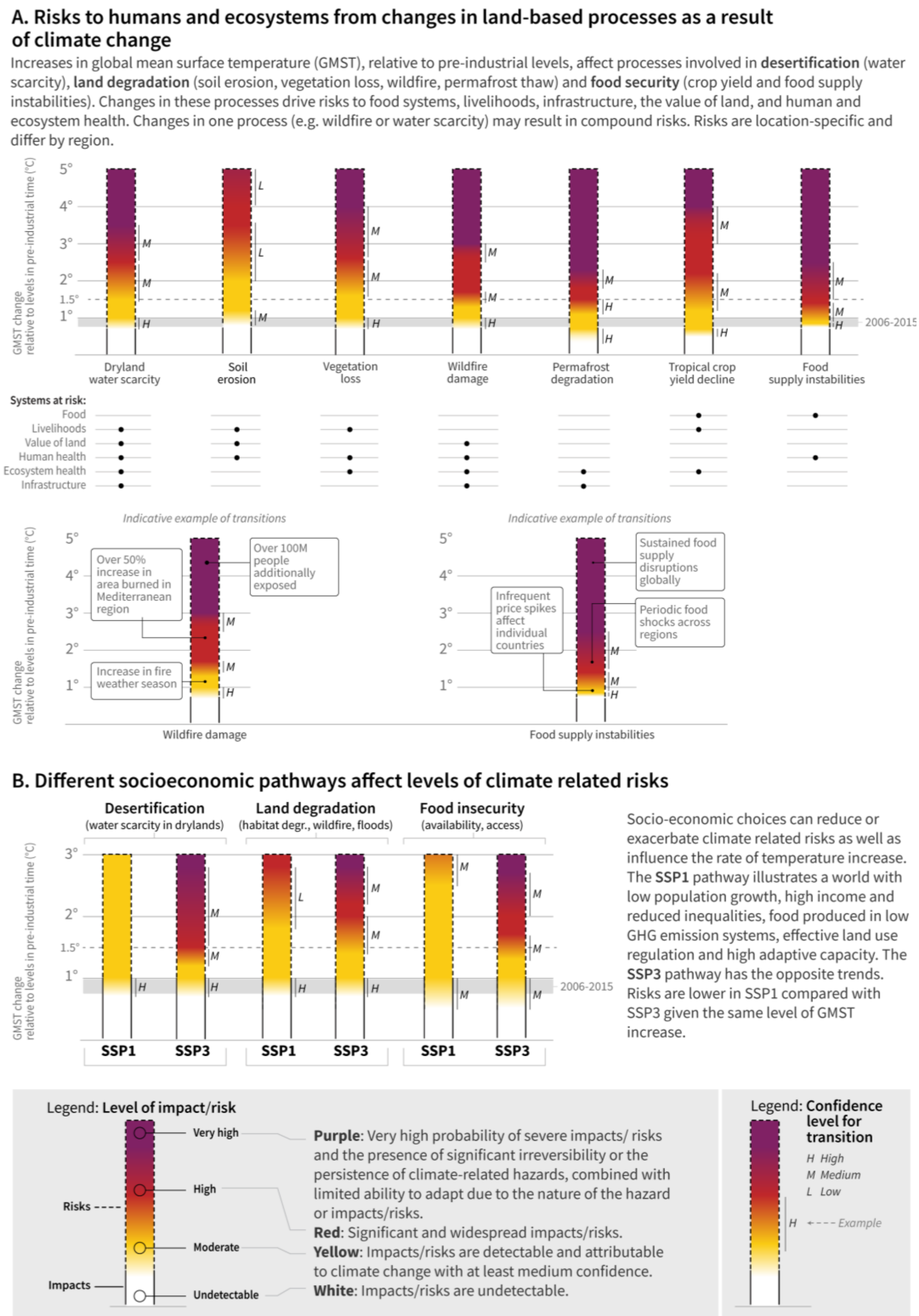

Figure 3: (fig SPM.2) ***Panel A**: **Risks to selected elements of the land system as a function of global mean surface temperature**. Links to broader systems are illustrative and not intended to be comprehensive. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway.* ***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) excluding the effects of targeted mitigation policies. Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change.*

2. Land as part of the solution

2.1. Mitigation, adaptation, combating desertification and land degradation, food security

2.1.1 Mitigation and adaptation options

- Response options for addressing climate change and other land-related challenges 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;
- Reduced deforestation and forest degradation could save 0.4-5.8 GtCO2-eq yr^{-1}, a shift towards plant-based diets 0.7-8.0 GtCO2-eq yr^{-1} and reduced food and agricultural waste 0.8-4.5 GtCO2-eq yr^{-1};
- While some response options have immediate impacts, others take decades to deliver measurable results.

Some land-related actions are already being taken that contribute to climate change adaptation, mitigation and sustainable development. A number of response options have been found to deliver benefits for adaptation, mitigation, ⇒desertification and ⇒land degradation, food security and sustainable development. There is *high confidence* that 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.

Cropland and livestock

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.

Diets

There is *high confidence* that consumption of healthy and sustainable diets (high in coarse grains, pulses, fruits and vegetables, nuts and seeds; low in energy-intensive animal-sourced and discretionary foods; with a carbohydrate threshold) presents major opportunities for reducing GHG emissions from food systems and improving health outcomes. There is *robust evidence* with *high agreement* that reducing meat consumption, and particularly beef, has a strong mitigation potential. This is because cattle is the main source of global livestock emissions (65-77%). Meat (sometimes specified as ruminant meat, mainly beef) is the single food with the greatest impact on the environment, most often in terms of GHG emissions and/or land use per unit commodity. For example, in the USA, 4% of food sold (by weight) is beef, which accounts for 36% of food-related emissions. A 15% reduction of animal products in the diets of high-income countries by 2050 would contribute to containing the need to expand agricultural output due to upward global demographic trends; the technical mitigation potential of an extreme no-animal-products scenario is up to 8 GtCO2-eq yr^{-1}, compared to a 'business-as-usual' scenario (note that this also includes CO2 removals from land sparing). Not only would GHG emissions and the pressure on land and water be significantly reduced but the potential for low-income countries to increase the intake of animal-based food, with beneficial nutritional outcomes, could be enhanced. Moreover, there is *medium confidence* that by 2050, dietary changes could free several million km^2 of land. Nevertheless, consumer choice and dietary preferences are guided by social, cultural, environmental, and traditional factors as well as economic growth, potentially hindering transformations to food systems.

Food loss and waste[1]

There is *medium confidence* that combined food loss and waste amount to 25–30% of total food produced and has tripled during the last 50 years: 540 Mt in 1961 to 1630 Mt in 2011. During 2010–2016, there is *medium confidence* that global food loss and waste contributed 8–10% of total anthropogenic GHG emissions, costing about 1 trillion USD2012 per year. A large share of produced food is lost in developing countries due to poor infrastructure (e.g., lack of refrigeration), while a large share of produced food is wasted in developed countries; in 2007, around 20% of the food produced went to waste in Europe and North America, while around 30% of the food produced was lost in Sub-Saharan Africa. The mitigation potential of reduced food loss and waste from a full life-cycle perspective (considering both food supply chain activities and land-use change) is estimated as 4.4 GtCO2-eq yr^{-1}. For example, halving food loss and waste reduces the global need for cropland area by around 14% and GHG emissions from agriculture and land-use change by 22–28% compared to the baseline scenarios by 2050. Furthermore, in addition to degraded health conditions, over-consumption (defined as food consumption in excess of nutrient requirements, additional to food waste) also leads to GHG emissions; in Australia for example, it accounts for about 33% GHGs emissions associated with food.

Carbon dioxide removal

⇒Carbon dioxide removal (CDR) includes mostly ⇒afforestation, ⇒reforestation, soil ⇒carbon sequestration in croplands and grasslands, ⇒direct air carbon capture and storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS). BECCS is the process of extracting ⇒bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere. These

[1] Food loss is defined as the reduction of edible food during production, postharvest, and processing, whereas food discarded by consumers is considered as food waste.

options, particularly reforestation and BECCS, require large areas of land and therefore strongly increase land competition.

Mitigation potential of response options

Estimates of the technical potential of individual response options are not necessarily additive. The largest potential for reducing AFOLU emissions is through reduced deforestation and forest degradation (0.4-5.8 GtCO2-eq yr^{-1}), a shift towards plant-based diets (0.7-8.0 GtCO2-eq yr^{-1}) and reduced food and agricultural waste (0.8-4.5 GtCO2-eq yr^{-1}). Agriculture measures combined could mitigate 0.3-3.4 GtCO2-eq yr^{-1}. The options with largest potential for CDR are afforestation/reforestation (0.5-10.1 GtCO2-eq yr^{-1}), soil carbon sequestration in croplands and grasslands (0.4-8.6 GtCO2-eq yr^{-1}) and BECCS (0.4-11.3 GtCO2-eq yr^{-1}).

Timescale of response options

Some response options, such as the conservation of high-carbon ecosystems such as peatlands, wetlands, rangelands, mangroves and forests, have immediate impacts. Meanwhile, there is *high confidence* that other options take decades to deliver measurable results, such as afforestation and reforestation as well as the restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils.

While peatlands can sequester carbon for centuries, there is also *high confidence* that land-based options that deliver ⇒carbon sequestration in soil or vegetation (afforestation, reforestation, agroforestry, soil carbon management on mineral soils, or carbon storage in harvested wood products) do not continue to sequester carbon indefinitely. When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, there is *high confidence* that the annual removal of CO2 from the atmosphere declines towards zero, while carbon stocks can be maintained. However, accumulated carbon in vegetation and soils is found with *high confidence* to be at risk from future loss (or sink reversal (⇒see carbon sink)) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management.

Applicability and efficacy of response options

The applicability and efficacy of response options have been found with *high confidence* to be 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. There is *high confidence* that response options are limited by land type, bioclimatic region, or local food system context, and that 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.

2.1.2 Land-based mitigation in 1.5°C pathways and consequences for the climate system

- The Paris Agreement goals most likely cannot be achieved without land-based mitigation such as ⇒CDR;
- Undue reliance on land-based mitigation options are associated with multiple feasibility and sustainability constraints such increasing food insecurity related to increasing land competition;

- There is considerable variation across modelled scenarios in the degree and direction of land use change, which depend both on the mitigation target set and on the trajectory of socio-economic development.

There is *high confidence* that 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 reduced deforestation, ⇒bioenergy, and carbon dioxide removal (CDR) such as ⇒reforestation, ⇒afforestation, and ⇒BECCS.

Land-based mitigation

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, although there is considerable uncertainty in this estimate.

Large-scale land-based mitigation is associated with multiple feasibility and sustainability constraints. For example, there is *medium confidence* that 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. Moreover, a particular challenge for land-based mitigation is ensuring that projects achieve a real reduction in emissions or enhancement of removals. 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 is assessed with *medium confidence* to take several harvest cycles to 'pay-back' the carbon emitted during conversion, from decades to over a century.

It is possible to achieve climate change targets with lower need for CDR, and even no reliance on technological CDR such as BECCS, but such scenarios rely on very steep near-term emission reductions across all sectors, including through agricultural demand-side changes (diet change, waste reduction), changes in agricultural production such as agricultural intensification, as well as rapid increases in energy and material efficiency. These scenarios also rely on earlier deployment of CDR in the form of afforestation/reforestation, requiring large areas of land. In contrast, there is *high confidence* that delayed mitigation action would increase reliance on land-based CDR.

Figure 4 shows six alternative pathways (archetypes) for achieving ambitious climate targets (RCP2.6 and RCP1.9), highlighting land-based strategies and GHG emissions. It illustrates the differences in timing and magnitude of land-based mitigation approaches including afforestation and BECCS. Besides their consequences on mitigation pathways and land consequences, those archetypes can also affect multiple other sustainable development goals that provide both challenges and opportunities for climate action, as demonstrated in section 2.1.4.

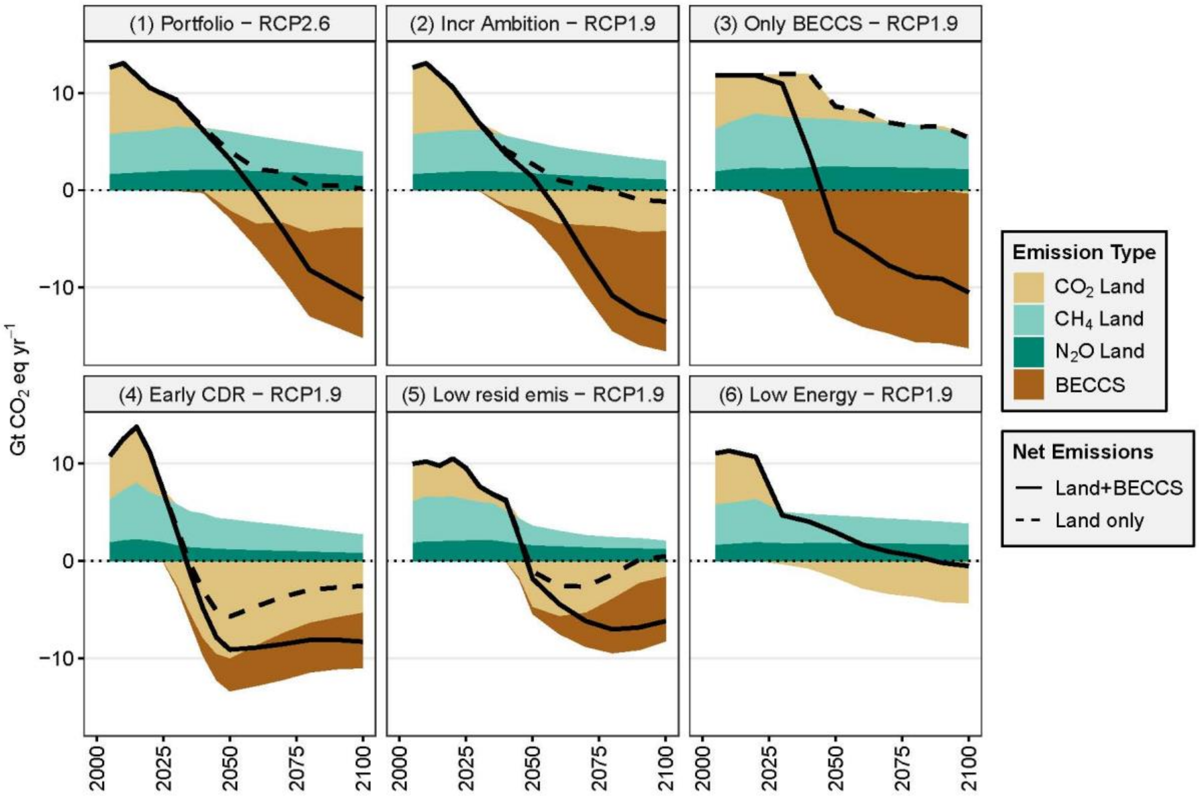

Figure 4: (fig 2.27) ***Evolution and breakdown of global land-based GHG emissions and removals under six alternative mitigation pathways****. This figure illustrates the differences in timing and magnitude of land-based mitigation approaches including afforestation and BECCS. All pathways are based on different IAM realizations of SSP2. Pathway 1 is based on RCP 2.6, while all other pathways are based on RCP 1.9. The categories CO_2 Land, CH_4 Land and N_2O Land include GHG emissions from land-use change and agricultural land use (including emissions related to bioenergy production). In addition, the category CO_2 Land includes negative emissions due to afforestation. BECCS reflects the CO_2 emissions captured from bioenergy use and stored in geological deposits. Solid lines show the net effect of all land based GHG emissions and removals (CO_2 Land, CH_4 Land, N_2O Land and BECCS), while dashed lines show the net effect excluding BECCS. CH_4 and N_2O emissions are converted to CO_2-eq.*

Consequences for the climate system of land-based mitigation options

Across a range of scenarios in 2100, CDR is delivered by both afforestation (median values of -1.3, -1.7 and -2.4 GtCO2yr^{-1} for scenarios RCP4.5, RCP2.6 and RCP1.9 respectively) and BECCS (-6.5, -11 and -14.9 GtCO2 yr^{-1} respectively). Nevertheless, the ⇒Integrated Assessment Models that produce these scenarios mostly neglect the biophysical effects of land-use on global and regional warming and tend not to include all possible CDR options such as ⇒DACCS and other nature-based solutions such as soil carbon sequestration.

There is *high confidence* that local and regional climates are affected by land-mitigation options through biophysical effects. Expansion of forest area, for example, typically removes CO2 from the atmosphere and thus dampens global warming, but the biophysical effects (such as changes in ⇒albedo or in the water cycle caused by changes in land cover) can dampen or enhance regional warming depending on location, season and time of day. During the growing season, afforestation is found with *high confidence* to generally bring cooler days from increased ⇒evapotranspiration, and warmer nights. During the dormant season, forests are warmer than any other land cover, especially in snow-covered areas where forest cover reduces albedo. In addition, there is *medium confidence* that trees locally dampen the amplitude of heat extremes.

There is considerable variation across modelled scenarios in the degree and direction of land use change. Land use change depends not only on the mitigation target set, but also on the trajectory of socio-economic development (as described with the SSPs). Modelled pathways limiting global warming to 1.5°C and 2°C project with *medium confidence* a 2 million km^2 reduction to a 12 million km^2 increase in forest area in 2050 relative to 2010. 3°C pathways project with *medium confidence* lower forest areas, ranging from a 4 million km^2 reduction to a 6 million km^2 increase. There is *high confidence* that 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.

2.1.3 Synergies between measures

- There are great synergies between measures that contribute to climate change adaptation and mitigation and those that combat ⇒desertification and ⇒land degradation and enhance food security;
- Nevertheless, the risk of maladaption or exceedance of adaptation limits remains high.

Combating desertification

Avoiding, reducing and reversing desertification (through, for example, regionally specific water harvesting and micro-irrigation, restoring degraded lands using drought-resilient ecologically appropriate plants, or agroforestry) would enhance soil fertility, increase carbon storage in soils and biomass, while benefitting agricultural productivity and food security (*high confidence*). Hence, there is *high confidence* that 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. Moreover, synergistic measures such as management of rangeland and forest fires and avoiding deforestation help eradicate and ensure food security.

Nevertheless, there is currently a lack of knowledge of adaptation limits and potential maladaptation to combined effects of climate change and desertification: there is *high confidence* that, at the moment, the potential for residual risks and maladaptive outcomes is high. Environmental impacts can occur from some adaptation options. For example, irrigation can cause soil salinisation or over-extraction, leading to ground-water depletion.

Combating land degradation

There is *very high confidence* that sustainable land management, including sustainable forest management, can prevent and reduce ⇒land degradation, maintain land productivity, sometimes reverse the adverse impacts of climate change on land degradation, and additionally also contribute to mitigation and adaptation.

For example, growing green manure crops and cover crops, crop residue retention, reduced/zero tillage, and maintenance of ground cover through improved grazing management are management options that reduce vulnerability to soil erosion and nutrient loss (*very high confidence*). There is *high* *confidence* that farming systems such as agroforestry, perennial pasture phases and use of perennial grains can substantially reduce erosion and nutrient leaching while at the same time having mitigation co-benefits by building soil carbon.

Reducing deforestation and forest degradation lowers GHG emissions. There is *high confidence* that sustainable forest management, which aims to provide timber, fiber, biomass, non-timber resources and other ecosystem functions and services, can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) by providing long-term livelihoods for communities, and can contribute to adaptation. Moreover, there is *high confidence* that sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest ⇒carbon sinks, including by transferring carbon to wood products.

Nevertheless, even with the implementation of measures intended to avoid, reduce or reverse land degradation, there is *high confidence* that some impacts of climate change on land degradation cannot be avoided. Examples of climate change induced land degradation that may exceed limits to adaptation include coastal erosion exacerbated by sea level rise where land disappears, thawing of permafrost affecting infrastructure and livelihoods, and extreme soil erosion causing loss of productive capacity.

Value chain management options

There is *high confidence* that options such as increased food productivity, dietary choices, reduced post-harvest losses, and waste reduction, can reduce demand for land conversion, thereby potentially freeing land and creating opportunities for enhanced implementation of other response options (see Figure 5). In the meantime, these options contribute to eradicating poverty and eliminating hunger while promoting good health and wellbeing.

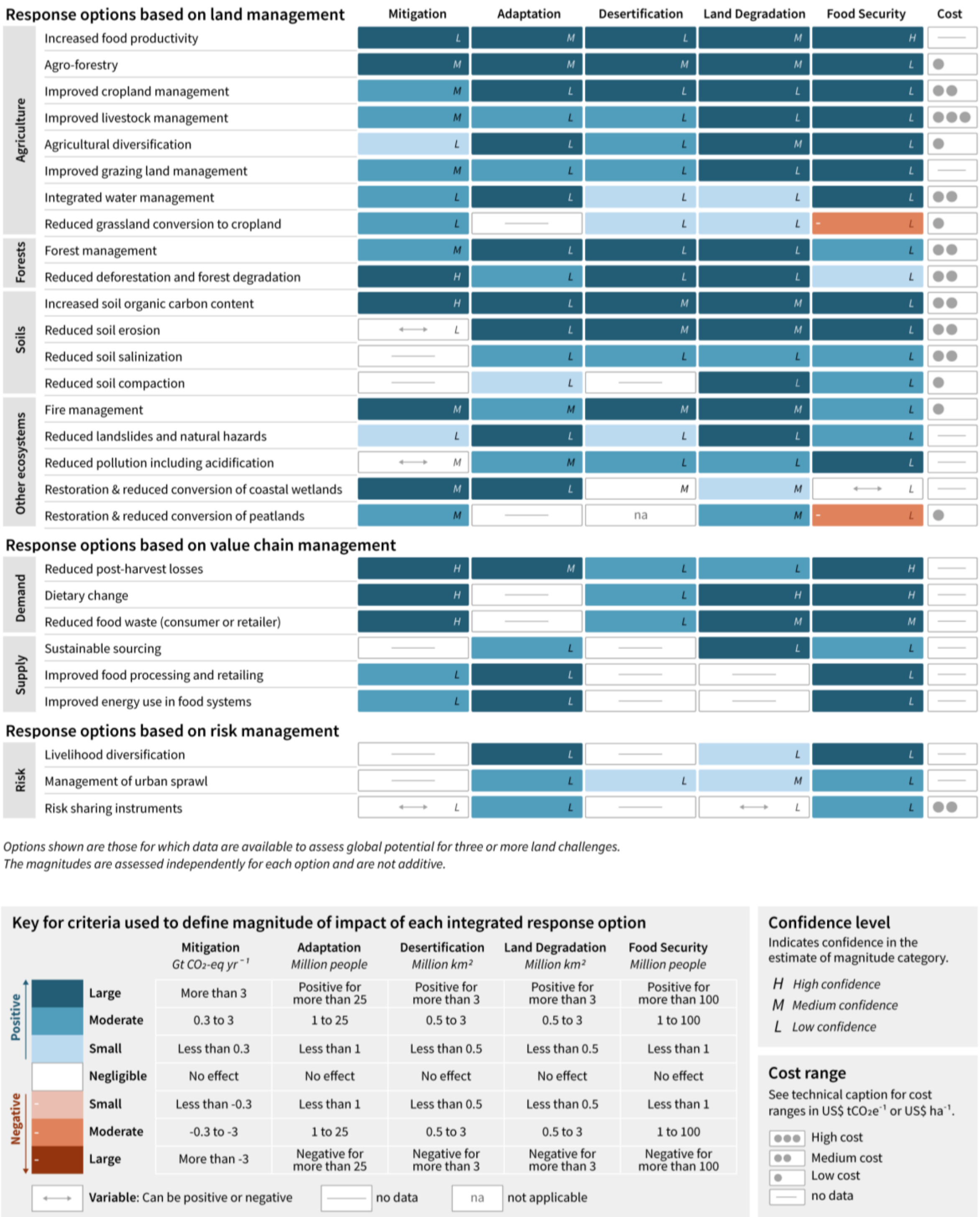

Figure 5: (fig SPM.3A) ***Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security****. This figure shows response options that can be implemented without or with limited competition for land, including some 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.*

2.1.4 Potential synergies and trade-offs of land-based mitigation with sustainable development, and dependence on context and scale

- Options that demand high levels of land conversion such as ⇒BECCS can exacerbate the risks for food insecurity, loss of ecosystem services and water scarcity, risks being much higher under SSP3 than under SSP1;
- Nevertheless, if implemented well, land-based mitigation could have several co-benefits with sustainable development.

Context and scale

While some land-based mitigation response options, such as reducing deforestation, can have many synergies and co-benefits, some responses pose risks associated with the effectiveness and potential adverse side-effects of measures chosen. For example, adverse side-effects on food security, ecosystem services and water security increase with the scale of BECCS deployment, because of the large level of land conversion required. There is *high confidence* that 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, such as ⇒afforestation. As shown with the green boxes of Figure 6, some practices can have synergies; for example, deployment of bioenergy on marginal land can benefit ⇒land degradation. Afforestation and biochar offer benefits in terms of food supply, reforestation and forest restoration. If implemented in previously forested areas and assuming a small-scale deployment with native species, these practices could reduce illegal logging.

Bioenergy

At large scales, ⇒bioenergy is expected to increase competition for land, water resources and nutrients, thus exacerbating the risks of food insecurity, loss of ecosystem services and water scarcity. These risks depend on the socioeconomic trajectory. In SSP3 the competition for land is exacerbated compared to SSP1 due to higher food demand from larger population growth and higher consumption of meat-based products. For SSP1, there is *medium confidence* that transitions from low to moderate risk for food security, land degradation and water scarcity in dry lands occur between 1 to 4 million km^2 of bioenergy or BECCS. There is *very high confidence* that all risk transitions occur at lower bioenergy levels in SSP3. In this pathway, land-based mitigation is therefore assessed with *medium confidence* to be strongly limited by sustainability constraints such that moderate risks occur already between 0.5 and 1.5 million km^2. There is *medium confidence* that a bioenergy footprint beyond 4 to 8 million km^2 would entail very high risk with strong decline in sustainability indicators, and an increase in the population at risk of hunger of well above 100 million.

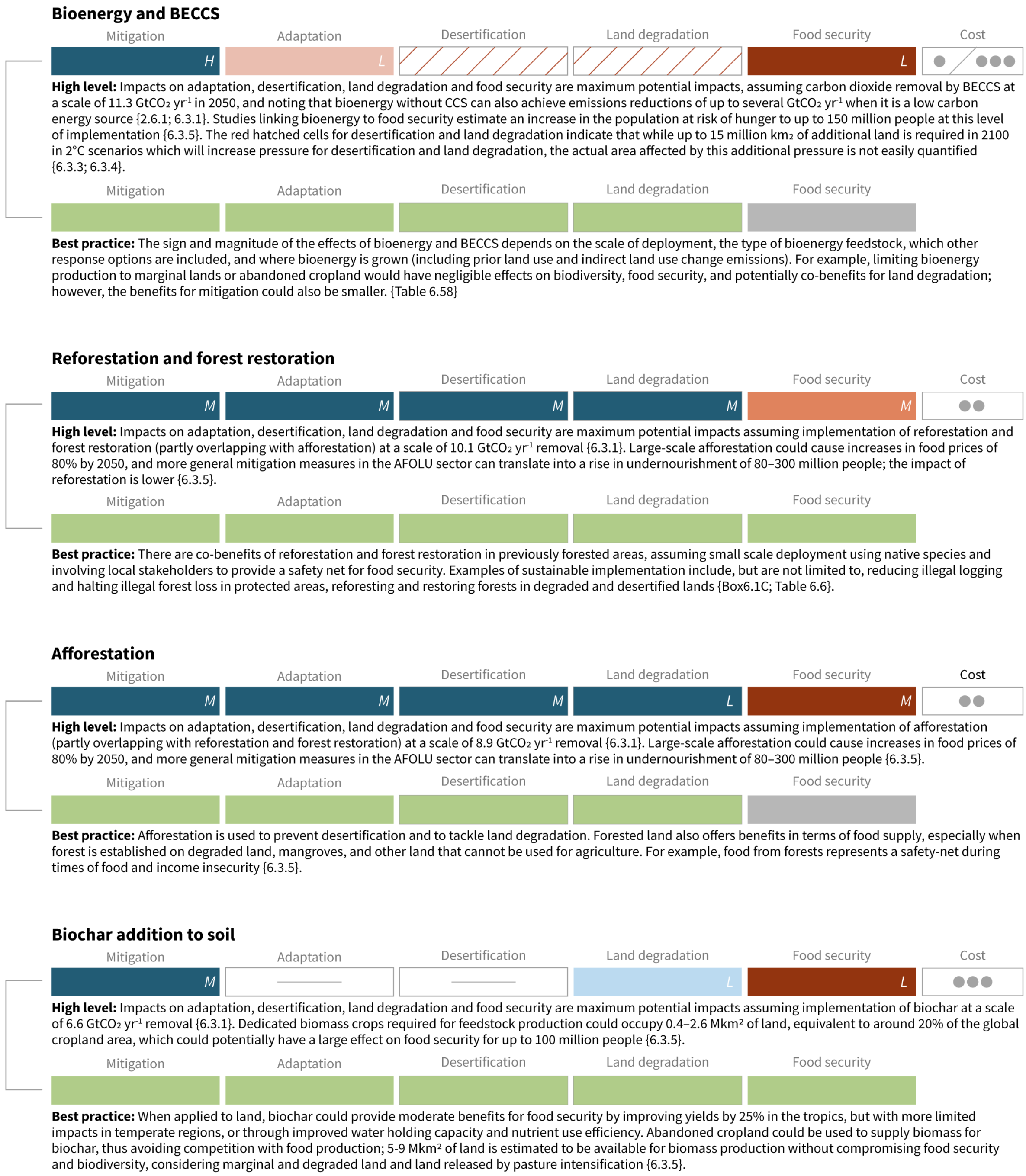

Figure 6: (fig SPM.3B) ***Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security****. This figure shows response options that rely on additional land-use change and could have implications across three or more land challenges under different implementation contexts. For each option, the first row (high level implementation) shows a quantitative assessment (as in Figure 5) of implications for global implementation at scales delivering CO2 removals of more than 3 GtCO2 yr^{-1} using the magnitude thresholds shown in Figure 5. 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.*

2.2. Enabling response options

2.2.1. Conditions for the implementation of measures

- Coordinated action is required across a range of actors, including businesses, producers, consumers, land managers, indigenous peoples and local communities and policymakers, at different scales, to create enabling conditions for adoption of response options.
- Response options need sufficient funding, institutional support, local buy-in, and clear metrics for success, among other necessary enabling conditions, to overcome many barriers to implementation.

There is *high confidence* that coordinated action is required across a range of actors, including businesses, producers, consumers, land managers, indigenous peoples and local communities and policymakers to create enabling conditions for adoption of response options. The response options are assessed to 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, land and food sectors are assessed with *medium confidence* to face particular challenges of institutional fragmentation, and often suffer from a lack of engagement between stakeholders at different scales.

Moreover, 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, could deliver improved results in addressing the complex challenges of sustainable land management and climate change (*high confidence*). 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.

There is *high confidence* that early action has challenges including technological readiness, upscaling, and institutional barriers. Some land-based response options are found with *high confidence* to have technological barriers that may limit their wide-scale application in the near term. Some response options, such as ⇒BECCS, have only been implemented at small-scale demonstration facilities. There is *medium confidence* that economic and institutional barriers, including governance, financial incentives and financial resources, limit the near-term adoption of many response options. '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 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.

2.2.2. Including women, indigenous peoples, local communities in decision-making

- Many sustainable development efforts fail because of a lack of attention to societal issues, including inequality, discrimination, social exclusion and marginalisation; - If women had the same access to productive resources as men, the number of hungry people in the world could be reduced by 12–17%; - Indigenous and local knowledge can play a key role in decision-making at various scales and levels, which could also promote their rights to self-determination.

There is *medium confidence* that a gender-inclusive approach offers opportunities to enhance the sustainable management of land. Women play a significant role in agriculture, food security and rural economies globally, forming 43% of the agricultural labour force in developing countries, ranging from 25% in Latin America to nearly 50% in Eastern Asia and Central and South Europe and 47% in Sub-Saharan Africa. At the same time, women constitute less than 5% of landholders (with legal rights and/or use- rights) in North Africa and West Asia, about 15% in Sub-Saharan Africa, 12% in Southern and Southeastern Asia, 18% in Latin America and Caribbean, 10% in Bangladesh, 4% in Nigeria. Indeed, in many world regions, laws, cultural restrictions, patriarchy and social structures such as discriminatory customary laws and norms have been found to 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, with *medium confidence*, support the alleviation of ⇒land degradation, and facilitate the take-up of integrated adaptation and mitigation measures. There is *high confidence* that secure land title and/or land access and control for women increases sustainable land management (SLM) by increasing women's conservation efforts, increasing their productive and environmentally beneficial agricultural investments, such as willingness to engage in tree planting and sustainable soil management as well as improving cash incomes. In 2011, the FAO found that if women had the same access to productive resources as men, the number of hungry people in the world could be reduced by 12–17%.

There is *high confidence* that indigenous and local knowledge (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**.** 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. Across diverse agro-ecological systems, ILK is found with *high confidence* to be the basis for traditional practices to manage the landscape and sustain food production, while delivering co-benefits in the form of biodiversity and ecosystem resilience at a landscape scale. Flexibility and adaptiveness are hallmarks of such systems, and documented examples include: traditional integrated watershed management in the Philippines; widespread use of terracing, with benefits in cases of both intensifying and decreasing rainfall; management of water harvesting and local irrigation systems in the Indo-Gangetic Plains. 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. Moreover, improving the participation of indigenous peoples in decision-making processes can promote their rights to self-determination.

2.2.3. Drivers of land-use change under different socio-economic development pathways

- The change in land differs depending on the SSP, thus on the policies implemented;
- SSP1 needs less agricultural land than other SSPs, leaving more room for ⇒reforestation, ⇒afforestation and ⇒bioenergy.

Future development of socio-economic factors and policies influence the evolution of the land–climate system, among others, in terms of the land used for agriculture and forestry. Thus, there is *high confidence* that policies such as crop and livelihood insurance, agriculture extension services, or agricultural production subsidies (among others) can play a major role in reducing the vulnerability and exposure of human and natural systems to climate change through land management. Figure 7 shows the projected change in land under SSP1, 2 and 5, at RCP1.9 :

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.

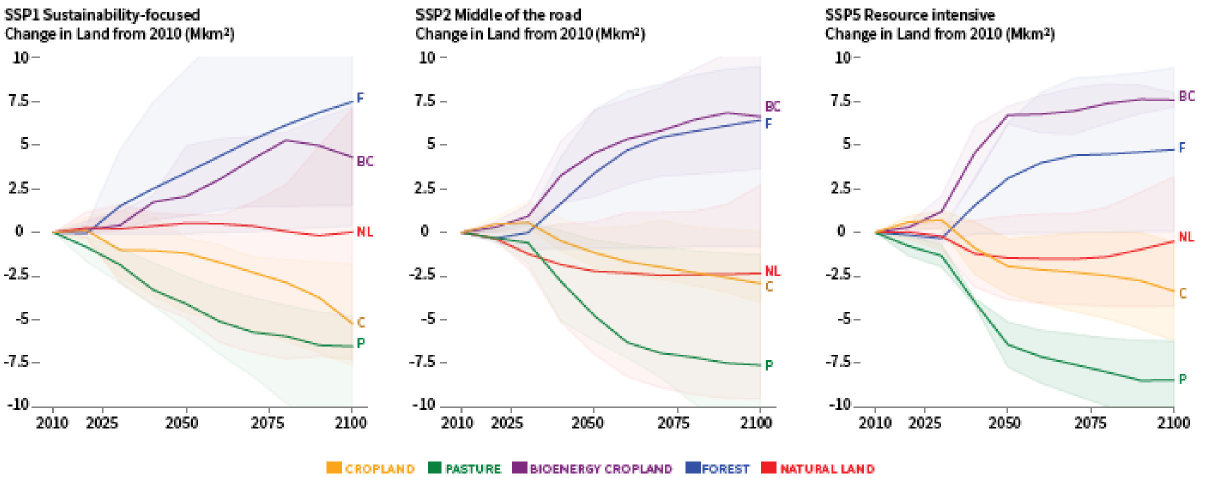

Figure 7: (fig SPM.4, panel A) ***Pathways linking socioeconomic development, mitigation responses and land****. The Shared Socioeconomic Pathways (SSPs) span a range of different socioeconomic assumptions. They are combined with Representative Concentration Pathways (RCPs) which imply different levels 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.*

In SSP1, sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption.

This land can instead be used for reforestation, afforestation and bioenergy. SSP2 shows an increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation, that decreases availability of agricultural land for food, feed and fibre.

SSP3 has a large population and strongly declining rates of crop yield growth over time, resulting in increased agricultural land area; the scenario is not represented here because the 1.9 $W.m^{-2}$ target was found to be infeasible in the SSP3 world. The combination of baseline emissions development, technology options, and policy support makes it much easier to reach the climate targets in the SSP1 scenario than in the SSP3 scenario.

3. The need for ambitious short-term action

3.1. Urgent action needed across all sectors, including (but not limited to) the land sector

Prompt action on climate mitigation and adaptation aligned with sustainable land management and sustainable development could reduce the risk to millions of people from ⇒climate extremes, ⇒desertification, ⇒land degradation and food and livelihood insecurity.

Rapid reductions in anthropogenic GHG emissions across all sectors following ambitious mitigation pathways is assessed to reduce negative impacts of climate change on land ecosystems and food systems (*medium confidence*). There is *high confidence* that 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. Moreover, ⇒carbon dioxide removal options – such as ⇒reforestation, ⇒afforestation, ⇒bioenergy and ⇒BECCS – are used to compensate for unavoidable emissions in other sectors; delayed action will, with *high confidence*, result in larger and more rapid deployment later.

Acting now may avert or reduce risks and losses and generate benefits to society (medium confidence). There is *high confidence* that prompt action on climate mitigation and adaptation aligned with sustainable land management and sustainable development could reduce the risk to millions of people from climate extremes, desertification, land degradation and food and livelihood insecurity. For example, there is *high confidence* that early warning systems for extreme weather and climate events are critical for protecting lives and property and enhancing disaster risk reduction and management, and that they are, alongside with seasonal forecasts, critical for food security (famine), biodiversity monitoring (including pests and diseases) and adaptive climate risk management.

3.2. Co-benefits associated with near-term action

- The economic costs of action on sustainable land management, mitigation, and adaptation are less than the consequences of inaction for humans and ecosystems;

- Investments in land restoration can result in global benefits and investments in drylands can have benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services.

There is *high confidence* that 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. 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, with *medium confidence*, to adaptation, mitigation, and development co-benefits through preserving ecosystem functions and services.

Moreover, there is *high confidence* that acting early will avert or minimise risks, reduce losses and generate returns on investment. The economic costs of action on sustainable land management, mitigation, and adaptation are assessed to be less than the consequences of inaction for humans and ecosystems (*medium confidence)*. For example, policy portfolios that make ecological restoration more attractive and 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.

There is *medium confidence* that investments in land restoration can result in global benefits and investments in drylands can have benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services. 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 are found with *high confidence* to 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.

Upfront investments in sustainable land management practices and technologies can range from about US$20 ha^{-1} to US$5000 ha^{-1}, with a median estimated to be around US$500 ha^{-1}. There is *high confidence* that government support and improved access to credit can help overcome barriers to adoption, especially those faced by poor smallholder farmers. There is *medium confidence* that near-term change to balanced diets can reduce the pressure on land and provide significant health co-benefits through improving nutrition.

3.3. Trade-offs associated with deferring action

- The potential for land-based response options will decrease with deferring action;
- Irreversible loss in land ecosystem functions and services required for food, health, habitable settlements and production could result from delayed action.

In future scenarios, deferral of GHG emissions reductions is assessed with *medium confidence* to imply trade-offs leading to significantly higher costs and risks associated with rising temperature. There is *high confidence* that 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. For example, failure to mitigate climate change will increase requirements for adaptation and may reduce the efficacy of future land-based mitigation options.

Indeed, the potential for some land management options decreases as climate change increases; for example, there is *high confidence* that climate alters the ⇒carbon sink capacity for soil and vegetation ⇒carbon sequestration, reducing the potential for increased soil organic carbon. Other options (e.g., reduced deforestation and forest degradation) prevent further detrimental effects to the land surface; there is *medium confidence* that delaying these options could lead to increased deforestation, conversion, or degradation, serving as increased sources of GHGs and having concomitant negative impacts on ecosystem services. 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.

There is *high confidence* that delaying action as is assumed in high emissions scenarios also includes 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. It could result in irreversible impacts in some ecosystems, which in the longer-term is assessed to have the potential to lead to substantial additional GHG emissions from ecosystems that would accelerate global warming (*medium confidence*).

4. Hot topics since the SRCCL and beyond

Tree restoration potential: The global tree restoration potential, Bastin et al., 2019[1] & responses

In this study, the authors find that under the current climate, there is room for an extra 0.9 billion hectares of canopy cover (cumulative tree cover, excluding existing trees and agricultural and urban areas). After considering their effect on five carbon pools (aboveground and belowground plant biomass, soil, litter, and dead wood), the authors claim that these additional trees could store 205 GtC (uncertainty range: 133.2-276.2 GtC) in areas that would naturally support woodlands and forests (i.e. allowing ecosystems to recover to a natural state, including ecosystems with 0% of tree cover). To interpret their potential to offset future emissions, it needs to be kept in mind though that about half of each emitted tC can be absorbed by land and oceans while the rest – the airborne fraction – remains in the atmosphere. As a reference, historical cumulative anthropogenic emissions amount to ~600 GtC. However, the potential estimated by Bastin et al. (2019) does not take into account sustainability limits to afforestation (substantial tree plantation in prairie or savanna ecosystems could for example be detrimental to biodiversity), or its potentially negative side-effects via albedo or evapotranspiration changes, which could lead to local warming.

Bastin et al. (2019) also estimated that the global potential canopy cover could shrink by around 223 million hectares by 2050. This decrease has been criticised for being too pessimistic because of the difficulty to account for the physiological response of forests to future climate changes and elevated CO_2 concentration with the statistical approach which the authors used.

This study has also been widely criticised to misleadingly suggest that "global tree restoration is our most effective climate change solution to date". This sentence has subsequently been removed from the abstract by the authors, who acknowledged that their work "does not preclude the urgent need to reduce greenhouse gas emissions from the combustion of fossil fuels, from deforestation and forest degradation."

Implementation challenges for reforestation policies: Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity, Heilmayr et al., 2020[2]

This paper assesses the carbon and biodiversity impacts of subsidy driven plantation expansion in Chile between 1986 and 2011 (for nearly a century, the Chilean government has provided strong and consistent policy support for ⇒afforestation). A comparison of simulations with and without subsidies indicates that payments for afforestation increased tree cover through expansion of plantations of exotic species but decreased the area of native forests. Thus, the authors found Chile's forest subsidies probably decreased biodiversity without increasing total carbon stored in aboveground biomass. The carbon benefit of subsidized plantation expansion was offset by the associated decline in more carbon-dense native forests, resulting in a modest, net decrease (46 ± 87 ktC) in carbon stored in aboveground biomass. In addition, given that plantation forests contain lower species richness than native forests, they found subsidies resulted in a decline in Chile's area-weighted standardized species richness. They also find that perfectly enforced restrictions on subsidy payments for previously forested lands could have increased carbon storage by 618.97 ktC while mitigating 78% of the subsidy's biodiversity losses,

[1] Bastin, J. F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M., & Crowther, T. W. (2019). The global tree restoration potential. *Science*. https://doi.org/10.1126/science.aax0848

[2] Heilmayr, R., Echeverría, C., & Lambin, E. F. (2020). Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. *Nature Sustainability*. https://doi.org/10.1038/s41893-020-0547-0

and could have increased the climate benefits of the subsidy from a loss of US$0.39x10^6 to a gain of US$4.84x10^6. "These results emphasize that strong, well-enforced safeguards for natural ecosystems can improve climate and biodiversity benefits of afforestation incentives, while reducing their costs."

Equity dimensions and carbon dioxide removal

Fair-share carbon dioxide removal increases major emitter responsibility, Fyson et al., 2020[1]

Meeting the Paris Agreement's goal cannot be achieved without ⇒carbon dioxide removal (CDR). Generally, a least-cost approach (minimizing global costs) is used to allocate CDR deployment among regions, while approaches on how to share this burden based on equity are lacking. Hence, in this study, the authors use two equity-based approaches to assess a fair-share CDR allocation between regions in 1.5°C and 2°C mitigation pathways: the 'cumulative per capita emissions' (CPCE), which assumes that countries with the highest cumulative emissions (since 1990) per person should shoulder more of the CDR burden, and the 'ability to pay' (AP) approach, that assumes that governments with more resources (higher GDP per capita) are more capable of paying for CDR deployment. They find that with these approaches, fair share outcomes for the USA, EU and China could imply 2-3 times larger CDR responsibilities this century compared with a global least-cost approach. Results are shown in Figure 8:

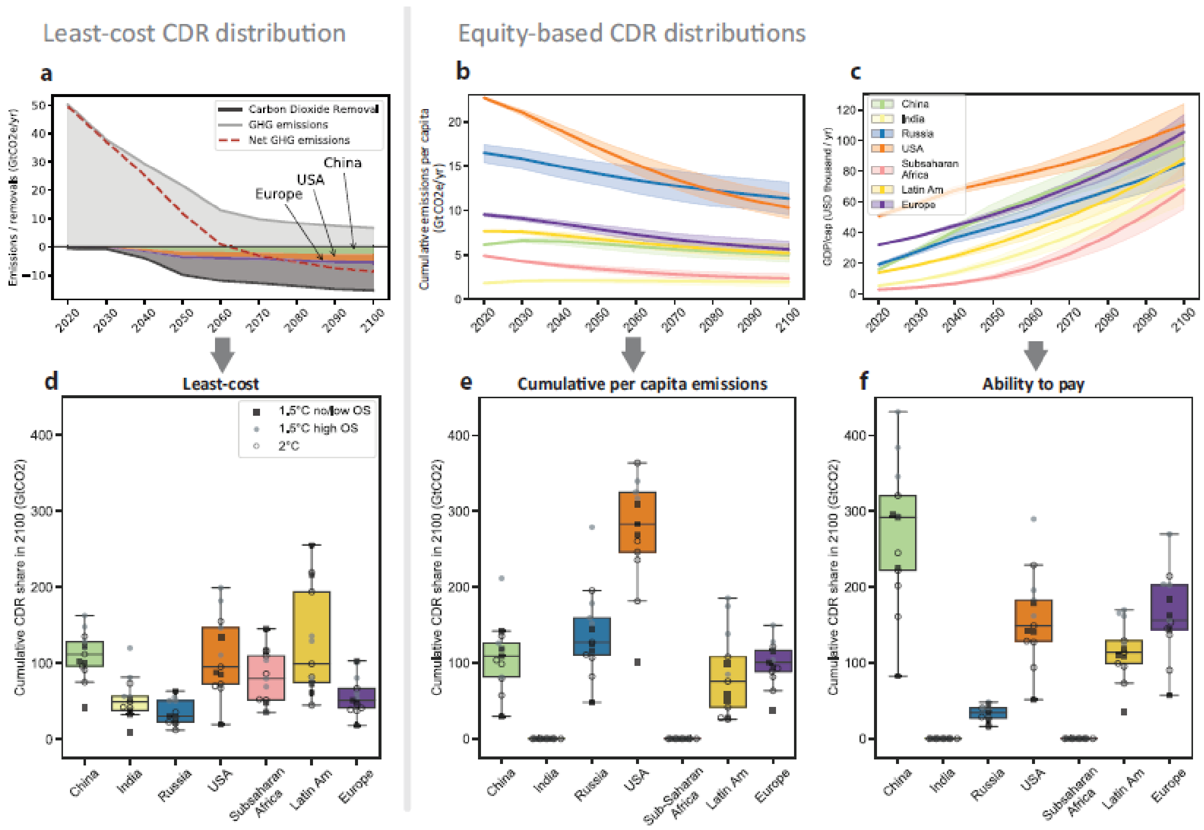

*Figure 8: **Illustration of CDR distribution under different equity approaches. a,** GHG emissions and removals for an illustrative mitigation pathway. The regional contribution of China (light green) and the USA (orange) are highlighted as part of the total CDR (blue). **b, c** Temporal evolution of cumulative emissions per capita and GDP per capita underlying the "cumulative per*

[1] Fyson, C. L., Baur, S., Gidden, M., & Schleussner, C.-F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nature Climate Change*. https://doi.org/10.1038/s41558-020-0857-2

capita emissions" (CPCE) and "ability to pay" (AP) equity approaches for seven world regions under the same illustrative pathway; shaded areas show the spread across assessed least-cost pathways. ***d,*** *Regional distribution of CDR for assessed least-cost pathways.* ***e, f*** *Regional distribution based on the CPCE and AP equity approaches, respectively. Symbols show results for pathways that limit warming to 1.5°C with no or limited overshoot (squares), overshoot 1.5°C by a high margin (closed circles) and that limit end-century warming to 2°C (open circles). Colored bars show the median, 25 and 75 percentiles across all pathways, with whiskers to the 5 and 95 percentiles.*

Moreover, delaying near-term mitigation affects the CDR responsibility of major emitters, illustrating "the burden that each region's next generations could inherit if their governments do not put stronger near-term mitigation measures in place." They estimate that if China, the US and the EU were to halve their 2030 target emission levels (consistent with what is required globally to limit warming to 1.5°C), their cumulative CDR burdens would respectively fall by about 20-65% (130-420 GtCO2), 30-57% (160-250 GtCO2) and 24-71% (40-120 GtCO2) (depending on the equity scheme).

Equity in allocating carbon dioxide removal quotas, Pozo et al., 2020[1]

This study follows a similar approach to Fyson et al., 2020: it uses the 'responsibility' principle (based on past emissions), the 'capability' principle (GDP per capita), and the 'equality' principle, corresponding to an equal per capita CDR. This last criterion would require Asia to provide most of the CDR, with India and China accounting for more than 28% of the CDR required. Concerning the EU, the authors find that quotas vary greatly across principles, from 33 to 325 GtCO2 allocated to the EU. But due to biophysical limits, only a handful of countries could meet their quotas acting individually (see Figure 9). The CDR options considered here are ⇒direct air carbon capture and storage, ⇒reforestation and ⇒bioenergy with carbon capture and storage, which are options that require biomass resources and carbon storage capacity, which some countries lack.

They conclude: "These results support strengthening cross-border cooperation while highlighting the need to urgently deploy CDR options to mitigate the risk of failing to meet the climate targets equitably."

[1] Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N., & Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change*. https://doi.org/10.1038/s41558-020-0802-4

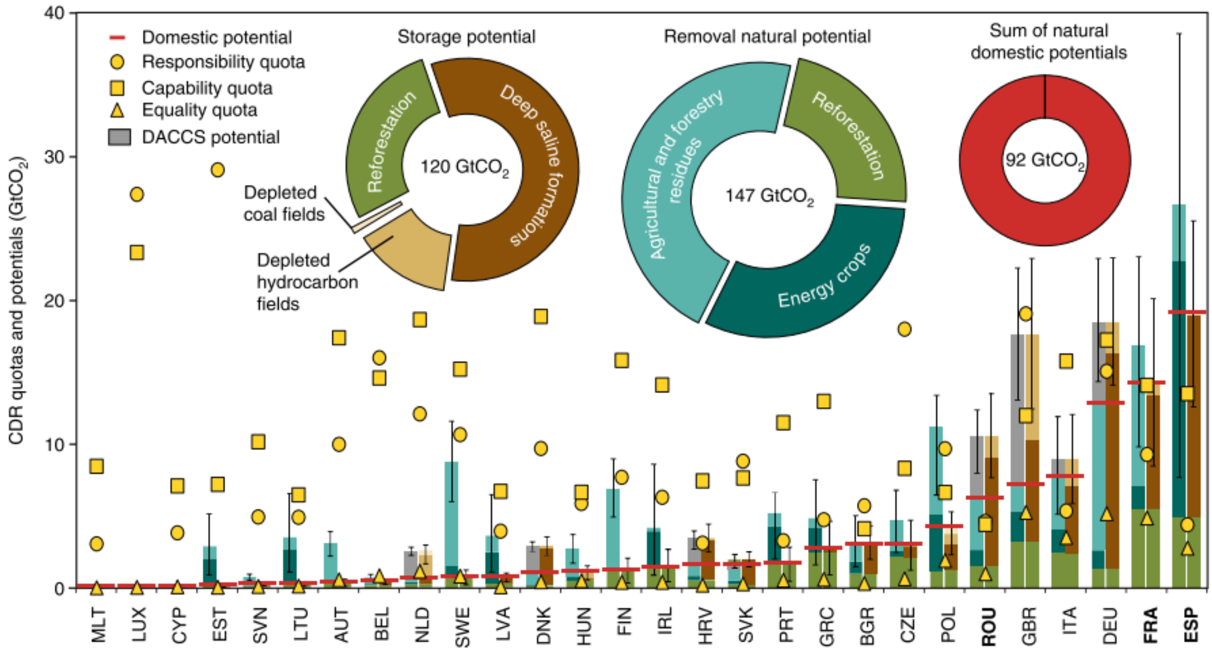

Figure 9: ***Comparison between the CO2 removal and storage potentials in each EU country and the quotas derived from the equity principles****. National CDR quotas for each principle are depicted with different markers (circles for Responsibility, squares for Capability and triangles for Equality). The domestic CDR potential for each EU member state is given by the vertical bars, where the left-hand side stacked bars denote removal potential (energy crops, forestry and agricultural residues and reforestation plus DACCS) and the right-hand side stacked bars provide the CO2 storage potential (deep saline formations, depleted hydrocarbon fields and coal fields as well as reforested areas). Countries are sorted in increasing order of their natural domestic potential considering the most limiting factor between removal and storage (depicted by a horizontal red line). Aggregated EU potentials are also provided with pie charts, which follow the same colour code as the bars. Country labels in bold indicate sufficient CDR natural potential to meet quotas in all cases. Error bars depict the conservative and optimistic scenarios for both removal and storage potentials in each country.*

Technical note

Shared Socio-economic Pathways

Shared socio-economic pathways (SSPs) are used in the IPCC special report on climate change and land (SRCCL) to explore implications of future socio-economic development on climate change mitigation, adaptation, and land-use. Based on five narratives the SSPs describe alternative socio-economic futures: sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5).

- 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 as a continuation of past trends, and only a gradual reduction in inequality. 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) (see below) which represent 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.

Representative Concentration Pathways

RCPs are scenarios that include time series 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. Each RCP is named after the ⇒radiative forcing they have at the end of the 21st century. For example, RCP2.6 describes a pathway where radiative forcing peaks at 3W/m2 and then declines to around

2.6W/m2 in 2100. Each RCP is only one of many possible scenarios that would lead to the specific radiative forcing characteristics.

RCP1.9 limits global warming to below 1.5 °C, the aspirational goal of the Paris Agreement. RCP2.6 represents a low emissions, high mitigation future, with a two in three chance of limiting global warming to below 2°C by 2100 in model simulations. RCP4.5 and RCP6.0 have intermediate levels of greenhouse gas emissions and result in intermediate levels of warming. RCP8.5 is a high greenhouse gas emissions scenario in the absence of policies to combat climate change, leading to continued and sustained growth in atmospheric greenhouse gas concentrations.

Due to uncertainties in feedback processes in the earth system, the response of the climate system to anthropogenic CO_2 emissions is subject to considerable uncertainty. The IPCC Fifth' Assessment Report estimates the ⇒transient climate response to cumulative CO_2 emissions to be between 0.2-0.7°C per 1000 Gt CO_2. **Error! Reference source not found.** provides the ranges of estimates of total warming since the pre-industrial period under four different RCPs. The uncertainty of the transient climate response is included in the uncertainty ranges.

	Near-term: 2031–2050		End-of-century: 2081–2100	
Scenario	Mean (°C)	*Likely* range (°C)	Mean (°C)	*Likely* range (°C)
RCP2.6	1.6	1.1 to 2.0	1.6	0.9 to 2.4
RCP4.5	1.7	1.3 to 2.2	2.5	1.7 to 3.3
RCP6.0	1.6	1.2 to 2.0	2.9	2.0 to 3.8
RCP8.5	2.0	1.5 to 2.4	4.3	3.2 to 5.4

Table 1: Projected global mean surface temperature change relative to 1850–1900 for two time periods under four RCPs.

IPCC’s calibrated language

The SRCCL uses IPCC calibrated language for the communication of confidence in the assessment process. This calibrated language uses qualitative expressions of confidence based on the robustness of evidence for a finding, and (where possible) uses quantitative expressions to describe the likelihood of a finding.

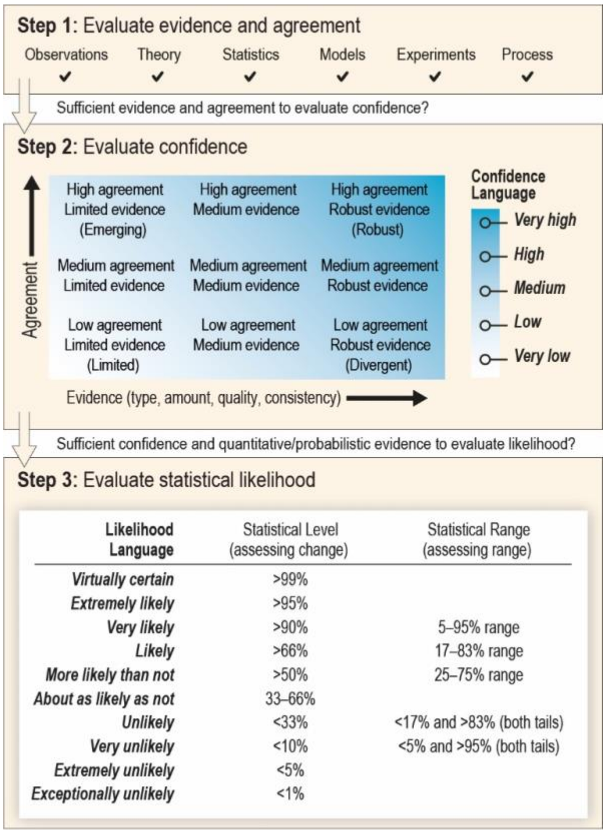

Figure 10: (fig TS.1) Schematic of the IPCC usage of calibrated language

Glossary

Aerosol A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm that reside in the atmosphere for at least several hours. The term aerosol includes both the particles and the suspending gas. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow- or ice-covered surfaces thereby altering their albedo and contributing to climate feedback.

Afforestation Conversion of land to forest that historically has not contained forests.

Albedo is a measure of how much sunlight that hits a surface or object is reflected without being absorbed. Something that appears white usually reflects most of the light that hits it and has a high albedo. Darker surfaces absorb more and have a low albedo which leads to warming of the surface. Clouds, snow and ice usually have a high albedo; soil surfaces cover the albedo range from high to low; vegetation in the dry season and/or arid zones can have high albedo, whereas photosynthetically active vegetation and the ocean have low albedo.

Bioenergy Is a form of renewable energy that is derived from biomass.

Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere. It uses the same technology as DACCS in that it stores the captured carbon in geological formations that permanently remove it from the atmosphere, thus resulting in negative emissions.

Carbon cycle The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide (CO2), carbon in biomass, and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is GtCO2 or GtC (Gigatonne of carbon = 1 GtC = 1015 grams of carbon. This corresponds to 3.667 GtCO2).

Carbon Dioxide Removal (CDR) Anthropogenic removal of atmospheric carbon dioxide and sequestration in geological, terrestrial or ocean reservoirs, or in products. CDR includes activities that enhance the natural carbon sinks but excludes natural CO2 uptake that is not directly caused by human activities.

Carbon sequestration The process of storing carbon in a carbon sink.

Carbon sink A reservoir (natural or human, in soil, ocean, and plants) where CO2 is stored.

CO_2 fertilisation The enhancement of plant growth as a result of increased atmospheric carbon dioxide concentration. The magnitude of CO_2 fertilisation depends on nutrients and water availability.

Climate extreme Is an extreme weather or climate event. An event that is rare at a particular place and time of year.

Desertification Land degradation in arid, semi-arid, and dry subhumid areas resulting from many factors, including climatic variations and human activities. Biological productivity is lost due to natural processes or induced by human activities whereby fertile areas become increasingly arid.

Direct air carbon capture and storage (DACCS) is a technology to capture CO2 from the atmosphere. The CO2 can be permanently stored in deep geological formations. When CO2 is geologically stored, it is permanently removed from the atmosphere, resulting in negative emissions.

Dust Bowl was a period (1930-1936) of severe dust storms that greatly damaged the ecology and agriculture of the American and Canadian prairies during the 1930s. Severe drought and a failure to apply dryland farming techniques to prevent the aeolian processes caused the phenomenon.

Evapotranspiration is the sum of water evaporation and transpiration from a surface area to the atmosphere. Evaporation accounts for the flow of water to the air from sources such as the soil, canopy interception, and water bodies. Transpiration accounts for the movement of water within a plant and the subsequent exit of water as vapor.

Forcing (or Radiative Forcing) Forcing is the change in the radiative flux, expressed in W/m2, at the tropopause or top of atmosphere due to a change in a driver of climate (for example the change in atmospheric CO2 concentration or in solar radiation.

Global mean surface temperature (GMST) Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions. Changes in GMST are usually expressed as departures from a value over a specified reference period.

Integrated Assessment Models (IAMs) are models that use storylines to construct alternative future scenarios of GHG emissions and atmospheric concentrations within a global socio-economic framework, including projections of AFOLU based on assumptions of, for example, crop yield, population growth and bioenergy use.

Land degradation A negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change. It is expressed as a long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans. This definition applies to forest and non-forest land. Changes in land condition resulting solely from natural processes (such as volcanic eruptions) are not considered to be land degradation.

NDC (Nationally Determined Contribution) A term used under the *United Nations Framework Convention on Climate Change (UNFCCC)* whereby a country that has joined the *Paris Agreement* outlines its plans for reducing its emissions. Some countries' NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve.

Negative emissions Removal of *greenhouse gases (GHGs)* from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural *carbon cycle* processes. See also CDR.

Net zero CO2 emissions Net zero *carbon dioxide (CO2)* emissions are achieved when *anthropogenic* CO2 emissions are balanced globally by anthropogenic CO2 removals over a specified period.

Net negative CO2 emissions A situation of net negative CO2 emissions is achieved when, as result of human activities, more *carbon dioxide is* removed from the *atmosphere* than is emitted into it. See also Negative emissions, Carbon Dioxide Removal and Net zero CO2 emissions.

Reforestation Conversion of land to forest that has previously contained forests but that has been converted to some other use.

Sensible heat is the heat that can be felt. It is the energy that moves from one system to another that changes the temperature rather than changing its phase.

Short-lived climate forcers Short-lived climate forcers refer to a set of compounds that are primarily composed of those with short lifetimes in the atmosphere compared to well-mixed / long-lived greenhouse gases. These are methane, ozone, aerosols and their precursors, and some halogenated species that are not well-mixed greenhouse gases. Short-lived climate forcers do not accumulate in the atmosphere at decadal to centennial time scales, and so their effect on climate is predominantly in the first decade after their emission, although their changes can still include long-term effects such as sea level change.

Tipping point Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible.

Transient Climate Response (TCR) Is a measure of the change in global mean surface temperature in response to a change in the atmospheric CO2 concentration or other forcing. The change in global mean surface temperature, averaged over a 20-year period, centred at the time of atmospheric CO2 doubling, in a climate model simulation in which CO2 increases at 1%/yr from preindustrial. It is a measure of the strength of climate feedbacks and the timescale of ocean heat uptake.

Transient Climate Response to cumulative CO2 emissions (TCRE) The change in transient global average surface temperature per unit cumulative CO2 emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO2 emissions and on the transient climate response (TCR).

CLIMATE
ANALYTICS