Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)

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Executive summary

As the global human population approaches a projected nine billion by 2035, pressure on land resources to deliver multiple, and often competing functions continues to intensify. Increased production of food, feed, fuel and fibre is expected to continue to exacerbate trade-offs with preservation of natural habitats, biodiversity conservation, continued provision of clean water, atmospheric regulation and nutrient cycling, all while the capacity of land to support these functions is threatened by climate change itself, biodiversity loss and land degradation (*high confidence*) {7.1, 7.6}.

The Agriculture Forestry and Other Land Use (AFOLU) sector is an important emissions source, accounting for 23% of global anthropogenic Greenhouse Gas (GHG) emissions (*high confidence*). However, land and biomass are also an important sink of CO_2 and CH_4. The natural sink is estimated to absorb around 31% of anthropogenic CO_2 emissions. Anthropogenic net CO_2 emissions and removals from AFOLU are estimated to be 5.7 ± 2.6 $GtCO_2$ yr^{-1} between 2009 and 2018, but when considering natural responses of land and land use is estimated be a net sink of -6.9 ± 4.0 $GtCO_2$ yr^{-1} (*medium confidence*). The overall trend is unclear, but according to reported gross and net values, the rate of deforestation, which accounts for a large proportion of AFOLU CO_2 emissions, has declined , with both global tree cover and overall total global forest growing stock reported to be stable (*medium confidence*). There are strong regional differences, generally losses in tropical regions and gains in temperate and boreal regions. The role of albedo, evapotranspiration and VOCs (and their mix) in the total climate forcing of land use is highly varying per bioclimatic region and management type. Average AFOLU CH_4 and N_2O emissions are estimated to be 144 $MtCH_4$ yr^{-1} and 6.8 MtN_2O yr^{-1} respectively between 2009 and 2018. There is *high confidence* that AFOLU CH_4 emissions continue to increase**,** with agriculture and specifically, enteric fermentation and to a lesser extent, rice cultivation remaining principle sources. Similarly, AFOLU N_2O emission continue to increase, with agriculture dominating emissions, notably from managed soils regarding manure application, deposition, and nitrogen fertiliser use (*high confidence*) {7.2, 7.3}.

AFOLU emission fluxes are driven by land use change and agriculture. Direct land use change drivers include commercial and smaller-scale agriculture expansion, unsustainable forest management, urbanisation and infrastructure development, wildfires and mining, while agriculture drivers include increases in livestock numbers, animal productivity, rice cultivation and nitrogen fertiliser use. However, these factors are ultimately determined by indirect drivers: human population dynamics, changes in affluence, consumption patterns and cultural norms, technological developments, institutions and governance (*high confidence*) {7.3}.

The AFOLU sector can reduce its greenhouse gas (GHG) emissions and provide land-based carbon dioxide removals (CDR) at scales that are important in the context of 1.5 and 2°C scenarios, while also providing renewable resources that facilitate mitigation in other sectors through substitution of fossil fuels and other GHG-intensive products (*high evidence, high agreement*). Significant near-term mitigation potential is available and at relatively low cost (*high evidence, high agreement*) but the AFOLU sector cannot provide more than approximately a third of the global mitigation needed for a 1.5 or 2°C pathway nor can it act as a cheap 'greenwashing' opportunity for (delayed) emission reductions in other sectors {7.1, 7.4, 7.5}.

Global sectoral studies suggest higher mitigation potential within AFOLU than integrated assessments, highlighting the wider portfolio of measures that are included in sectoral assessments, lower costs, as well as differences in approaches and assumptions. Nonetheless, the assessment confirms that AFOLU can make an important contribution to global mitigation. Global sectoral studies indicate AFOLU has supply-side (up to USD100/tCO_2-eq) mitigation potential of approximately 9 (± 3) $GtCO_2$-eq yr^{-1} between 2020 and 2050 (*medium confidence*). In contrast, integrated assessment models (IAMs) estimate AFOLU to have an average economic potential (up to USD100/tCO_2-eq) of 4.1 (-0.1 to 9.5) $GtCO_2$-eq yr^{-1} for the same period and 6.8 (-0.2 - 10.5) $GtCO_2$-eq yr^{-1} in 2050 (*medium confidence*). Differences between global sectoral assessments and IAMs are largely due to: (1) IAMs including a smaller portfolio of AFOLU measures compared to the sectoral estimates; (2) the baseline scenarios in some IAMs already include low carbon prices and seeing considerable mitigation, particularly from land-use change, which limits the mitigation potential in the USD100/tCO_2-eq yr^{-1} scenario; and (3) most IAM estimates including temperature over-shoot scenarios, placing most mitigation, particularly of CDR measures, after 2050 {7.4, 7.5}.

Between 2020-2050, mitigation measures in forests and other ecosystems provide the largest share of (up to USD100/tCO_2-eq) mitigation potential in AFOLU, followed by agriculture and demand-side measures (*high confidence*). In the sectoral assessment, reduced conversion (protection), enhanced management, and restoration of forests, wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester carbon by 6.1 (±2.9) $GtCO_2$-eq yr^{-1}, with measures that 'protect' having the highest mitigation densities (mitigation per area). Agriculture provides the second largest share of mitigation, with 3.9 ± 0.2 $GtCO_2$-eq yr^{-1} potential (up to USD100/tCO_2-eq), from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to healthy diets and reducing food waste, can provide 1.9 $GtCO_2$-eq yr^{-1} potential (accounting only for diverted agricultural production and excluding land-use change). Demand-side measures reduces agricultural land needs and land competition, which can complement and enable supply-side measures such as reduced deforestation and reforestation {7.4}.

Tropical regions are estimated to have greatest economic mitigation potential because of the lower cost of avoided deforestation and degradation, however there is also considerable potential in developed and emerging countries in temperate regions. Asia and the developing Pacific is estimated to have the greatest economic potential (33% of global potential) then Latin America and the Caribbean (25%), Africa and the Middle East (20%), Developed Countries (17%) and Eastern Europe and West-Central Asia (6%). The protection of forests and other ecosystems is the dominant source of mitigation potential in tropical regions, sequestering carbon through agriculture measures is important in Developed Countries and Eastern Europe and West-Central Asia, and demand-side measures are key in Developed Countries and Asia and developing Pacific. Generally, total AFOLU mitigation potential correlates with a country or region's land area, but many smaller countries and regions have disproportionately high levels of mitigation potential for their size {7.4}.

Land-based mitigation measures have important co-benefits, risks and trade-offs (*high confidence*). Considering the potential consequences of misguided or inappropriate land management, it is critical that AFOLU mitigation is pursued and associated measures are designed and implemented carefully and in such a way that maximises co-benefits, limits risks and avoids trade-offs. The results of implementing AFOLU measures is often variable and highly context specific. Depending on local and geographic conditions, scale of deployment and management, mitigation measures have potential to positively or negatively impact biodiversity, ecosystem functioning, air and water quality, land degradation, adaptation capacity, surface albedo or evapotranspiration effects, animal welfare, land use change, rights infringements and land tenure, food prices, food security, rural livelihoods, human wellbeing and contribution to SDGs. Integrated responses that contribute to mitigation and adaption, address poverty eradication and rural employment and development, and also address biodiversity loss and land degradation, while positively contributing to fibre and food security and other Sustainable Development Goals (SDGs), will be crucial (*high confidence*) {7.1, 7.4, 7.6}.

Very large-scale deployment of afforestation or biomass production for bioenergy *is likely* to be in conflict with environmental and social sustainability dimensions (*high confidence).* Bioenergy forms a crucial mitigation option, with capacity to substitute fossil fuels in a range of applications and also provide carbon dioxide removal (CDR), especially if biogenic CO_2 emitted from bioenergy use is captured and deposited in geological storage (BECCS). IAMs estimate that the CDR component of BECCS have a (up to USD100/tCO_2-eq) mitigation potential of 0.8 (0– 6.3) GtCO_2 yr^{-1} in 2050 (*medium confidence*). Some land-based mitigation measures, like BECCS, biochar and wood products, in addition to providing mitigation through emissions reduction and/or carbon storage, can also produce bioenergy and consumer or construction products, providing additional mitigation through the substitution of fossil fuels and/or other products (*high confidence*). However, such additional mitigation is not credited to AFOLU, but rather other sectors like energy and buildings. The capacity to substitute energy and materials in other sectors through dedicated lignocellulosic crops from AFOLU and accounting for food security, biodiversity and environmental constraints, is estimated to equate to approximately 40-150 EJ yr^{-1} in 2050 and requiring 120-500 Mha. The capacity from agriculture and forestry residues is estimated to be 4-57 EJ yr^{-1} by 2050, increasing to 50-90 EJ yr^{-1} by 2100 (*medium confidence*) {7.4}.

AFOLU mitigation measures have been known for decades, although increasing emissions, notably CH_4 and N_2O, indicate a lack of action and progress. Globally, the AFOLU sector has so far contributed modestly to net mitigation, as past policies have delivered 0.65 GtCO_2 yr^{-1} of mitigation during 2010-2019 or 1.4% of global gross emissions. The majority (>80%) resulted from forestry measures (*high confidence*). Considering trends in population, income, consumption of animal-sourced food, fertiliser use and disturbances from climate change, effective policy interventions and financing will be required for AFOLU to contribute to mitigation. Sustainable investments in the AFOLU sector are proportionately small compared to other sectors and do not match its potential contribution to climate mitigation. Although from bio-physical and ecological perspective, the mitigation potential of AFOLU measures is large, its feasibility is mainly hampered by lack of public acceptance of some measures, uncertainty over long term additionality, and lack of institutional capacity and long-term continuation of certain measures {7.6}.

Realisation of mitigation potential will require bold, concerted and sustained effort by all stakeholders, from policy makers and investors to land managers. Only USD 0.7 billion yr^{-1} is estimated to have been spent on AFOLU mitigation, well short of the more than USD 400 billion yr^{-1} that is estimated to be necessary to achieve up to 30% of global mitigation effort. This is not a large sum of money in comparison to current subsidies in agriculture and forestry; i.e. (gradual) redirection of some of those funds can contribute already positively to mitigation. Successful policies and measures include establishing tenure rights and community forestry, agriculture improvement and sustainable intensification, conservation, payments for ecosystem services, forest management improvement and certification, voluntary supply chain management efforts, private funding and regulatory efforts. The success of different policies, however, will depend on numerous region-specific factors in addition to funding, including governance, institutions, long term consistent execution of measures, and the specific policy setting {7.6}.

Transparency, credibility and accuracy in estimating and reporting GHG fluxes is critical to incentivise action (*high confidence*). A large ~5 GtCO_2 yr^{-1} gap exists on land fluxes between global models and country GHG inventories, mostly caused by differences in how the anthropogenic forest sink is defined: countries consider a much larger area of managed forest than global models, and on this area consider the fluxes due to human-induced environmental change to be anthropogenic while global models treat them to be natural. Adjusting global models results to be more compatible with countries'

GHG inventories will enable a more accurate assessment of collective progress towards the Paris Agreement's climate goals {7.2}.

Addressing the many knowledge gaps is crucial in advancing mitigation with AFOLU. In addition to on-going development of mitigation measures, such as CH_4 inhibitors or improved forest management techniques, research priorities include improved quantification of anthropogenic and natural GHG fluxes and emissions modelling, better understanding of the impacts of climate change on mitigation potential and general feasibility, permanence and additionality of estimated mitigation, monitoring, reporting and verification. There is need to include a greater suite of mitigation measures in IAMs, informed by spatially explicit marginal abatement cost curves (MACCs), while accounting for socio-economic factors, including cultural and institutional, and cross-sector trade-offs. Finally, there is critical need to research and develop appropriate country-level, locally specific, policy and land management response options that facilitate mitigation while also contributing to biodiversity conservation, ecosystem functioning, farmer income and wider SDGs {7.7}.

7.1 Introduction

As the global human population rapidly approaches a projected nine billion by 2035, the pressure on land to support multiple and often competing functions continues to intensify. Increased production of food, feed, fuel and fibre is expected continue to exacerbate the trade-offs with, preservation of natural habitats, biodiversity conservation, continued provision of clean water, atmospheric regulation and nutrient cycling, all while the capacity of land to support these functions is threatened by climate change itself, biodiversity loss and land degradation (Shukla et al. 2019; IPCC WGII). Accordingly, there has been significant attention given to the role of land and its management, including its vital contribution to climate change mitigation, both within academic, policy and practical spheres, as reflected by the IPCC.

7.1.1 Key findings from previous reports

In contrast to previous IPCC reports, the Fifth Assessment Report (AR5) combined Agriculture, Forestry and Other Land Use (AFOLU). This sector is unique due to its capacity to mitigate climate change through greenhouse gas (GHG) emission reductions, as well as removals (Smith et al. 2014). However, AFOLU was reported as accounting for almost a quarter of anthropogenic emission at that time, with three main GHGs associated with AFOLU; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Overall emission levels had remained similar since the publication of AR4. The diverse nature of the sector, its linkage with wider societal, ecological and environmental aspects and the required coordination of related policy, was suggested to make implementation of known and available supply-side and demand-side mitigation measures particularly challenging. Despite such implementation barriers, the considerable mitigation potential of AFOLU as a sector in its own right and its capacity to contribute to mitigation within other sectors, was emphasised, with land-related measures, including bioenergy, estimated as capable of contributing between 20 and 60% of the total cumulative abetment to 2030 identified within transformation pathways. There was *medium evidence* and *medium agreement* that supply-side agriculture and forestry measures had an economic (at USD 100/tCO_2-eq) mitigation potential of 7.2-10.6 GtCO_2-eq^{-1} in 2030 (using GWP_{100} and multiple IPCC values for CH_4 and N_2O) of which about a third was estimated as achievable at < USD 20/tCO_2-eq. Agricultural measures were reported as sensitive to carbon price, with cropland and grazing land management having greatest potential at USD 20/tCO_2-eq and restoration of organic soils at USD 100/tCO_2-eq. Forestry measures were less sensitive to carbon price, but varied regionally, with reduced deforestation, forest management and afforestation having greatest potential depending on region. Limited research prevented conclusive estimation of mitigation potential from demand-side measures. Overall, the dependency of mitigation within AFOLU on a complex range of factors, from population growth, economic and technological developments, to the sustainability of mitigation measures and impacts of climate change, was suggested to make estimation of mitigation potential, its regional distribution and realisation, highly challenging (Smith et al. 2014).

Building on AR5, the IPCC Special Report on Climate Change and Land (SRCCL) highlighted the mitigation potential within AFOLU but only in terms of global technical potentials and noted the constraints and challenges to its realisation (Shukla et al. 2019). Land can only be part of the solution alongside rapid emission reduction in other sectors. It was recognised that land supports many ecosystem services on which human existence, wellbeing and livelihoods ultimately depend, yet over-exploitation of land resources was reported as driving considerable and an unprecedented rate of biodiversity loss, land and wider environmental degradation. Urgent action to reverse this trend was deemed crucial in helping to accommodate the increasing demands on land and enhance climate change adaptation capacity. There was *high confidence* that global warming was already causing an increase in the frequency and intensity of extreme weather and climate events, impacting ecosystems, food security, wildfire regimes and land processes, with existing carbon stocks within soils and biomass at serious risk. The impact of land cover on regional climate (through biophysical effects) was also highlighted, although there was *no confidence* regarding impacts on global climate.

Since AR5, the share of AFOLU to anthropogenic GHG emissions had remained largely unchanged (23% - *medium confidence*), though uncertainty in estimates of both sources and sinks of CO_2, exacerbated by difficulties in separating natural and anthropogenic fluxes, was emphasised. Models indicated land to have *very likely* provided a net removal of CO_2 between 2007 and 2016. As in AR5, land cover change, notably deforestation, was identified as a major driver of anthropogenic CO_2 emissions and agriculture, a major driver of the increasing anthropogenic CH_4 and N_2O emissions.

In terms of mitigation, without reductions in overall anthropogenic emissions, increased reliance on large-scale land-based mitigation was predicted, which would add to the many already competing demands on land. However, some mitigation measures were suggested to not compete with other land uses, while also having multiple co-benefits, including adaption capacity and potential synergies with Sustainable Development Goals (SDGs). As in AR5, there was large uncertainty surrounding mitigation within AFOLU, in part because current carbon stocks and fluxes is unclear and subject to temporal variability, mitigation from individual measures is not necessary additive, while the applicability of measures is highly context specific. Many AFOLU measures were considered well-established and some achievable at low to moderate cost, yet contrasting economic driers, insufficient policy, lack of incentivisation and institutional support to stimulate implementation among the many stakeholders involved, including hundreds of millions of land owners and managers, in regionally, socially and economically diverse contexts, was recognised as hampering realisation of potential.

None the less, the importance of mitigation within AFOLU was highlighted, with modelled scenarios demonstrating the considerable potential role and land-based mitigation forming an important component of pledged mitigation in National Determined Contributions (NDCs) under the Paris Agreement. The sector was identified as the only one in which large-scale Carbon Dioxide Removal (CDR) may currently be possible (e.g. through afforestation/reforestation or soil carbon management). This CDR component was deemed crucial to limit climate change and its impacts, which would otherwise lead to enhanced release of carbon from land. Still, uncertainty surrounding the feasibility and sustainability of some related measures was noted. Several mitigation measures were reported as having technical potential of > 3 $GtCO_2$-eq yr^{-1} by 2050 *(high confidence)*. Changing agricultural management, reducing food loss and waste and a shifting diets to reduce the consumption of animal-sourced foods to more plant based diets (where appropriate), were suggested as having potential to reduce emissions and free land for other mitigation measures such as afforestation/reforestation. However, the SRCCL emphasised that mitigation cannot be pursued in isolation. The need for integrated response options, that tackle climate change, but also land degradation and desertification, while enhancing food security and contributing to other SDGs was made clear (Shukla et al. 2019).

7.1.2 Boundaries, scope and changing context of the current report

This chapter assesses GHG fluxes between land and the atmosphere due to AFOLU, the associated drivers behind these fluxes, mitigation response options and related policy, at time scales of 2030 and 2050. Land and its management has important links with other sectors and therefore associated chapters within this report, notably concerning the provision of food, feed, fuel or fibre for human consumption and societal wellbeing (Chapter 5), for bioenergy (Chapter 6), the built environment (Chapter 9), transport (Chapter 10) and industry (Chapter 11). Mitigation within these sectors may in part, be dependent on contributions from land and the AFOLU sector, with interactions between all sectors discussed in Chapter 12. This chapter also has important links with IPCC WGII, regarding climate change adaptation. Linkages are illustrated in Figure 7.1.

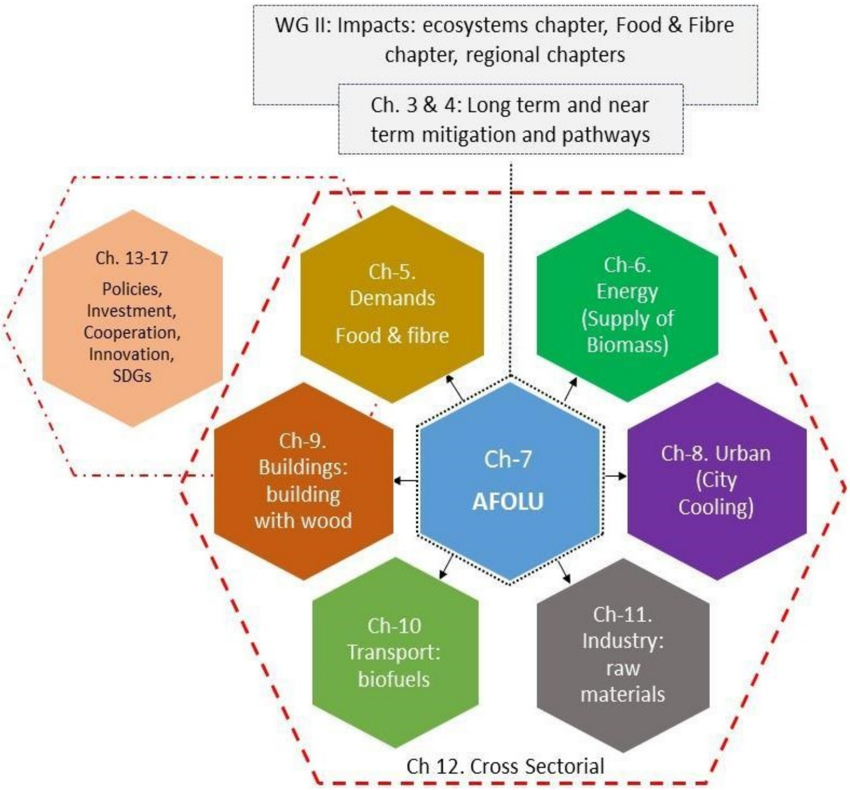

Figure 7.1 Linkage between Chapter 7 and other chapters within this report as well as the contribution of IPCC WGII to AR6. **Mitigation potential estimates in this chapter consider potential emission reductions and removals only from within the AFOLU sector itself, and not the substitution effects from biomass and biobased products in sectors such as Energy, Transport, Industry, Buildings, nor biophysical effects of e.g. cooling of cities.**

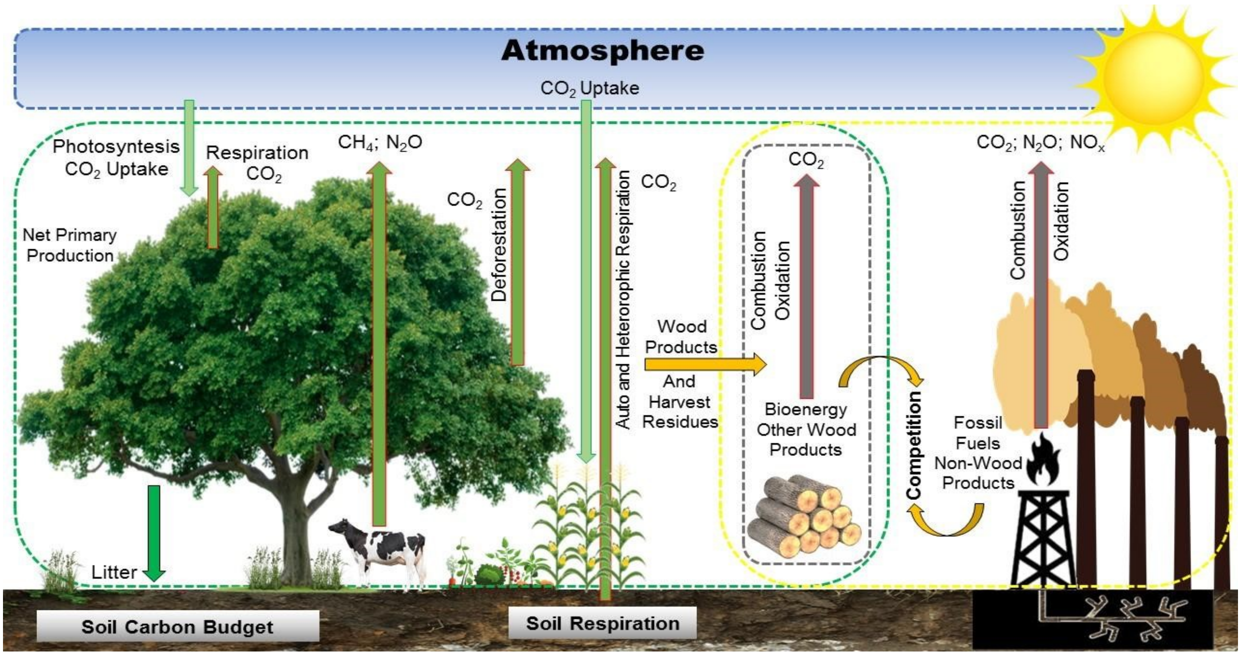

Figure 7.2 Summarised representation of interactions between land management, its products in terms of food and fibre, and land - atmospheric greenhouse gas fluxes

As highlighted in both AR5 and the SRCCL, there is complex interplay between land management and GHG fluxes as illustrated in Figure 7.2, with considerable variation in management regionally, as a result of geophysical, climatic, ecological, economic, technological, institutional and socio-cultural diversity. The capacity for land-based mitigation varies accordingly. The principal focus of this chapter is therefore, on evaluating regional land-based mitigation potential, identifying applicable AFOLU mitigation measures, estimating associated costs and exploring policy options that could enable implementation. Mitigation measures are broadly categorised as those relating to (1) forests and other ecosystems (2) agriculture (3) biomass production for bioenergy and (4) demand-side levers. Assessment is made in the context that land-mitigation is expected to contribute roughly 25% of the 2030 mitigation pledged in Nationally Determined Contributions (NDCs) under the Paris Agreement (Grassi et al. 2017), yet very few countries have provided details on how this will be achieved. In light of AR5 and the SRCCL findings, that indicate large land-based mitigation potential, considerable challenges to its realisation, but also a clear nexus at which humankind finds itself, whereby current land management, driven by population growth and consumption patterns, is undermining the very capacity of land, a finite resource, to support wider critical functions and services on which humankind depends. Mitigation within AFOLU is occasionally and wrongly perceived as an opportunity for in-action within other sectors. AFOLU simply cannot compensate for mitigation shortfalls in other sectors. As the outcomes of many critical challenges (UN Environment 2019), including biodiversity loss (IPBES 2019) and soil degradation (FAO and ITPS 2015), are inextricably linked with how we manage land, the evaluation of AFOLU, realisation of necessary adjustments and associated policy options, is crucial. This chapter aims to address three core topics;

1. What is the latest estimated mitigation potential of AFOLU measures according to both sectoral approaches and integrated assessment models, and how much of this may be realistic within each global region?
2. How do we realise the optimal mitigation potential, while minimising trade-offs and risks and maximising co-benefits that can enhance food security, conserve biodiversity and address other land challenges?
3. How effective have policies been so far and what additional policies or incentives might enable realisation of mitigation potential?

This chapter first outlines the latest trends in AFOLU fluxes, their sources and the methodology supporting their estimation in Section 7.2. Direct and indirect drivers behind emission trends are discussed in Section 7.3. Mitigation measures, their costs, co-benefits, trade-offs, estimated regional potential and contribution within integrated global mitigation scenarios, is presented in Sections 7.4 and 7.5. Associated policy responses, links with SDGs and implementation feasibility is explored in 7.6, with gaps in knowledge identified in Section 7.7.

7.2 Historical and current trends in GHG emission and removals; their uncertainties and implications for assessing collective climate progress

The land is a source and sink of CO_2 and CH_4 and a source of N_2O due to both natural and anthropogenic processes that happen simultaneously and are therefore difficult to disentangle (IPCC 2010; 2019a; 2019b). A range of methodological approaches and data have been applied to estimating AFOLU fluxes, each developed for their purposes and based on available data and methods. Since the SRCCL (IPCC 2019a, Jia et al. 2019), there are updated emissions estimates (Sections 7.2.2 and 7.2.3), while the assessment of biophysical processes and short-lived climate forcers (Section 7.2.4) is largely unchanged. Estimates of AFOLU flux and climate impacts remain subject to large uncertainties due to the difficulties in attribution, the different methodologies applied, and large uncertainties in the underpinning data (*high confidence*). Further progress has been made on the implications of differences in AFOLU emissions estimates for assessing collective climate progress (Section 7.2.2.5, Cross-Chapter Box 5)

7.2.1 Total net GHG flux from AFOLU

Broadly following National Greenhouse Gas Inventory (NGHGI) reporting under the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2006), the total anthropogenic AFOLU flux can be separated into: (i) net anthropogenic flux from Land Use, Land Use Change, and Forestry (LULUCF) (due to both change in land cover and land management), also referred to as FOLU in previous IPCC reports; and (ii) the net flux from Agriculture. Net fluxes of CO_2 (Section 7.2.2) are predominantly from LULUCF. Net fluxes of CH_4 and N_2O (Section 7.2.3), are predominantly from Agriculture (Table 7.1).

Table 7.1 Net anthropogenic emissions (averages for 2009-2018)[1] from Agriculture, Forestry, and other Land Use (AFOLU). Positive value represents emissions; negative value represents removals.

Direct Anthropogenic								Natural Response	
Gas	**Units**	**Net anthropogenic emissions due to AFOLU**			**Non-AFOLU anthropogenic GHG emissions[4,6]**	**Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas**	**AFOLU as a % of total net anthropogenic emissions by gas**	**Natural response of land to anthropogenic environmental change[5]**	**Net-land atmosphere flux**
		LULUCF	**Agriculture**	**Total**					
		A	**B**	**C = A+B**	**D**	**E = C+D**	**F = (C/E) *100**	**G**	**C+G**
CO_2[2]	Mt CO_2								
	Gt CO_2-eq yr^{-1}			**5.7 ± 2.6**	34.5 ± 1.8	40.0 ± 3.3	15%	-12.5 ± 3.2	-6.9 ± 4.0
CH_4[3,6]	Mt CH_4	19.2	143.7						
	Gt CO_2-eq yr^{-1}	0.6	4.6	**5.2**					
N_2O[3,6]	Mt N_2O yr^{-1}	0.3	6.8						
	Gt CO_2-eq yr^{-1}	0.1	1.8	**1.9**					
Total	**Gt CO_2-eq yr^{-1}**			**12.9**	**42.7**	**55.6**	**23.2%**		

[1] Estimates are only given until 2018 as this is the latest date when data are available for all gases, and consistent with Chapter 2. Positive fluxes are emission from land to atmosphere. Negative fluxes are removals.

[2] Net anthropogenic flux of CO_2 due to land cover change such as deforestation and afforestation, and land management including wood harvest and regrowth, peatland draining and burning, cropland and grassland management. Average of three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). Emissions are predominantly associated with the LULUCF sector. It is not possible to separate LULUCF and agriculture within the model results.

[3] Agricultural emission estimates show the mean and assessed uncertainty of three databases; EDGAR (Crippa et al. 2020), FAOSTAT (2019) and USEPA (2019) as relevant. Latest versions of databases indicate historic emissions to 2018, 2017 and 2015 respectively, with average values for the period calculated accordingly.

[4] Total non-AFOLU emissions are the sum of total CO_2-eq emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping and from the PRIMAP database for CH_4 and N_2O averaged over 2007-2014 only as that was the period for which data were available. [note to update with final numbers from chapter 2 including non-AFOLU CH_4 and N_2O]

[5] The natural response of land to human-induced environmental changes is the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change. The estimate shown represents the average from 17 Dynamic Global Vegetation Models with 1SD uncertainty (Friedlingstein et al. under review)

[6] All values expressed in units of CO_2-eq are based on AR6 100-year Global Warming Potential (GWP_{100}) values without climate-carbon feedbacks (CH_4 = 32, N_2O = 261).

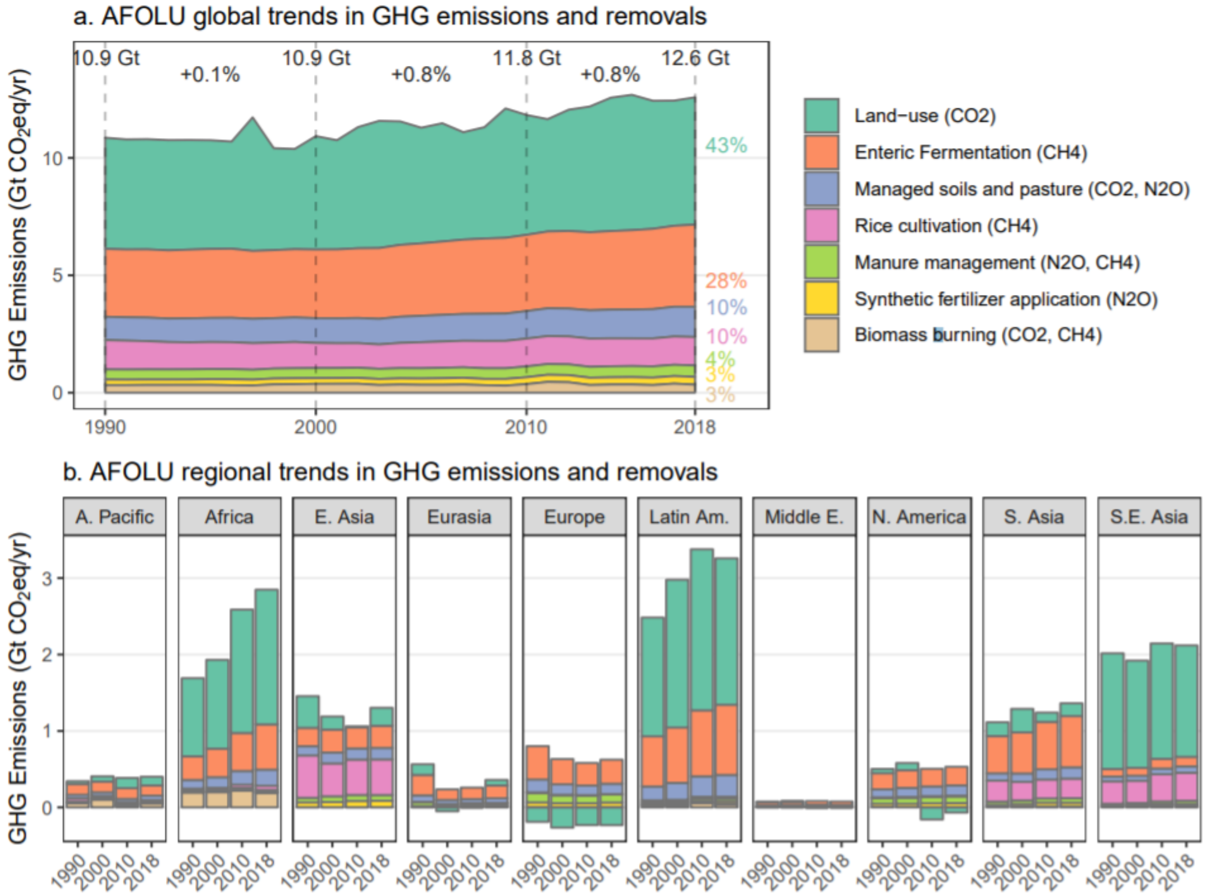

Figure 7.3 Global and regional net greenhouse gas (CO_2, CH_4 and N_2O) flux from Agriculture, Forestry and Other Land Use (AFOLU) 1990 to 2018. Positive values are emissions from land to atmosphere, negative values are removals. Panel a shows total anthropogenic GHG emissions in the AFOLU sector divided into major subsectors and gases. The indicated growth rates between 1990-2000, 2000-2010, 2010-2018 are annualised across each time period. Panel b shows regional emissions in the years 1990, 2000, 2010, 2018. Land-use CO_2 (green shading) represents all CO_2 emissions AFLOLU. It is the mean from three bookkeeping models (Hanis et al. 2015; Houghton and Nassikas 2017: Gasser et al. 2020). These include land cover change (e.g. deforestation, afforestation), forest management including wood harvest and regrowth, grassland management, agricultural management, peat burning and draining. [note: the predominant driver is deforestation]. Emissions of CH_4 and N_2O are from the EDGAR database (Crippa et al. 2019), including savannah burning emissions of CH_4 and N_2O from FAOSTAT (FAO 2020a). Supplemented with CH_4 and N_2O emissions from forest and peat fires taken from the Global Fire Emissions Database version GFED4.1s (Van der Werf et al. 2017). Note: Chapter 7 compares different data sets for CO_2, CH_4 and N_2O. For CO_2 the bookkeeping models give net emissions in the order of 6 $GtCO_2$ yr^{-1} higher in 2010-2017 than National Greenhouse Gas Inventories which show net AFOLU flux as near zero globally (emissions are balanced by removals). The causes and implications of this are discussed in Sections 7.2.2.1 and 7.2.2.5. For assessment of cross-sector

fluxes related to the food sector, see Chapter 12. See Annex B, Part III for a description of sources and the sector classification.

The total global net GHG emissions from AFOLU were 12.9 ± 2.9 $GtCO_2$-eq yr^{-1} around 23% of total global net anthropogenic GHG emissions over the period 2009-2018 (Table 7.1, Figure 7.3). This AFOLU flux is the net of anthropogenic emissions of CO_2, CH_4 and N_2O, and anthropogenic removals of CO_2 and CH_4. The global AFOLU net flux above is slightly higher than the 12.0 ± 2.9 $GtCO_2$-eq yr^{-1} for 2006-2016 presented in the SRCCL. Global emissions of CO_2 are predominantly due to LULUCF and have remained relatively constant over the past few decades (*low confidence*) (Section 7.2.2), while non-CO_2 emission from Agriculture have risen from 6.1 $GtCO_2$-eq yr^{-1} in the 1990s to 6.9 $GtCO_2$-eq yr^{-1} in 2009 to 2018 [note: uncertainties to be calculated with final updated numbers and confidence added] (Section 7.2.3). Trends going back further in time are discussed in WGI Chapter 5. Drivers are discussed in Section 7.3.

The relative contribution of AFOLU to total anthropogenic emissions has decreased from 31% in 1990 due to larger increases in emissions from the energy and other sectors (*high confidence*) (Chapter 2). AFOLU is the only sector to include sinks (CO_2 net sinks in Europe North America and Eurasia). The contribution of AFOLU to total emissions varies regionally: Latin America and Caribbean 58%; Africa 56%; South East Asia and developing Pacific 50%; Southern Asia 29%; Asia-Pacific developed 17%; Eurasia 11%; Eastern Asia 10%; Europe 9% North America 7%; and Middle East 3%.

To present a fuller understanding of the role of land as a natural sink for CO_2 emissions, we also assess the global net flux due to the natural response of land to human-induced environmental change ("indirect anthropogenic effects" (IPCC 2010), (Table 7.1, see Section 7.2.2). The land provided a natural sink service (*high confidence*) in removing a net flux of -12.5 ± 3.3 $GtCO_2$ yr^{-1} (*medium confidence*) from the atmosphere during 2009-2018, 31% of total anthropogenic emissions. Model results and atmospheric observations concur that, when combining natural and anthropogenic processes, the land was a global net sink for CO_2 (*high confidence*) with a modelled magnitude of -7.0 ± 4.0 $GtCO_2$ yr^{-1} (*medium confidence*) during 2009-2018 (Friedlingstein et al. under review).

7.2.2 Flux of CO_2 from AFOLU, and the non-anthropogenic land sink

7.2.2.1 Global net AFOLU CO_2 flux

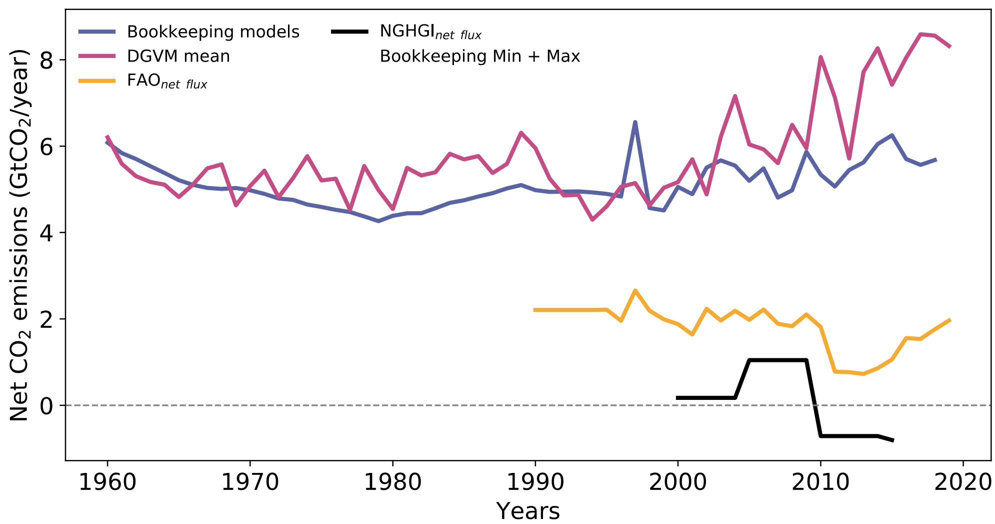

Figure 7.4 Global net CO_2 flux due to AFOLU estimated using different methods for the period 1960 to 2020 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. Purple line: the mean estimate

and minimum and maximum (purple shading) from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). These include land cover change (e.g. deforestation, afforestation), forest management including wood harvest and forest degradation, shifting cultivation, regrowth of forests following wood harvest or abandonment of agriculture, grassland management, agricultural management. Emissions from peat burning and draining are added from external data sets (see text). Pink line: the mean from 17 DGVMs runs all using the same driving data, together forming the TrendyV9 (Sitch et al. 2008) used within the Global Carbon Budget 2020 and including different degrees of management (see Appendix A in Friedlingstein et al. under review). Yellow line: data downloaded from FAOSTAT (http://www.fao.org/faostat/ - downloaded: November 2020), comprising: net emissions from (i) forest land converted to other land, (ii) net emissions from organic soils in cropland, grassland and from biomass burning (including peat fires and peat draining) and (iii) net emissions from forest land remaining forest land, which includes managed forest lands as well as forest degradation (Tubiello et al. 2020). Black line: Net emissions and removals estimate from National Greenhouse Gas Inventories (NGHGI) based on country reports to the UNFCCC for LULUCF (Grassi et al. 2020) which include land use change, and flux in managed lands.

Since the SRCCL (Jia et al. 2019) and AR5, there has been a major update of FAO Forest Resource Assessment (FRA) (Tubiello et al. 2020), the inclusion of a new model in the Global Carbon Budget estimates (Friedlingstein et al., subm.) as well as minor updates from the NGHGIs (Grassi et al. 2020). Comparison of estimates of the global net AFOLU flux of CO_2 from diverse approaches (Figure 7.4) shows *low confidence* in the mean flux and trend over the last few decades. For the decade 2009–2018[1], the AFOLU flux of CO_2 was 5.7 ± 2.6 $GtCO_2$ yr^{-1} (mean ± 1σ standard deviation, *likely* range) according to global models, approximately 15% of total anthropogenic CO_2 emissions (Friedlingstein et al. under review). The flux is the mean of three bookkeeping (carbon accounting) models that track changes in soil and vegetation carbon following land use change and land management (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). This is consistent with the mean of 17 Dynamic Global Vegetation Models (DGVMs) of 7.7 ± 1.8 $GtCO_2$ yr^{-1} (Friedlingstein et al. under review). In contrast, the AFOLU flux from NGHGIs for 2010-2017 was -0.2 ± 1.0 $GtCO_2$ yr^{-1} (i.e. a small sink) (Grassi et al. 2020). FAO estimates a net source of 1.3 $GtCO_2$ yr^{-1} (estimated uncertainties about 70%) for 2009-2018 (FAOSTAT, Tubiello et al. 2020).

While the mean of the bookkeeping model's global CO_2 net emissions have remained relatively constant since the 1960s individual bookkeeping models suggest opposite trends (Friedlingstein et al. under review). The DGVMs suggest an increase in net emissions the most recent decade, while FAO estimates show a small reduction in net emission and the NGHGIs suggest a trend from a small net source to a small net sink. Thus, we have *low confidence* in the trend in global net AFOLU CO_2 emissions

The reasons for the discrepancy between the estimated global net AFOLU flux in models and country reported data are largely due to different approaches to attributing fluxes due to environmental change on extant forest land as anthropogenic or natural (Grassi et al, 2018; Grassi et al, 2020 in press) (Section 7.2.2.5). Other reasons include driving data, inclusion of different processes and methodological approaches as discussed in more detail in the SRCCL (see also Gasser and Ciais 2013; Pongratz et al. 2014; Tubiello et al. 2015; Friedlingstein et al. under review).

Countries report NGHGI data with a range of methodologies, resolution and completeness, dependant on capacity and available data, consistent with IPCC guidelines and subject to an international review process (IPCC 2006, 2019). FAO FRA data are based on country reported gross and net forest area change and changes in carbon stock in "forest land" in five-year intervals. "Forest land" includes

FOOTNOTE: [1] Data is available until 2019 but shown here up to 2018 for consistency with other AFOLU GHG datasets. These may all be updated to 2019 depending on data availability for the final draft unmanaged natural forest, leading to possible overestimation of anthropogenic fluxes (Tubiello et al, 2020). FAO emissions estimates follow IPCC guideline methods (IPCC 2006), but only include carbon in living biomass. The new FAO FRA 2020 data (FAO 2020b) is more consistent with NGHGI submissions. In particular, FRA now estimates larger sinks in Russia since 1991, and in China and the USA from 2011, and larger deforestation emissions in Brazil and smaller in Indonesia than FRA 2015 (FAO, 2015; Tubiello et al, 2020). Globally, deforestation, both gross and net, has come down considerably between 2015 and 2020, but still an annual net deforestation of ~5 Mha yr^{-1} remains according to FAO (2020h). For the models: Houghton and Nassikas (2017) base their land use forcing primarily on FRA 2015; Hansis et al. (2015) and the DGVMs use the LUH2 data set (Hurt et al. 2020) or HYDE (Goldewijk et al. 2017a; 2017b) based on FAOSTAT (FAO 2020a) and FRA 2015 (FAO 2015); Gasser et al. (2020) use a combination of LUH2 and FRA 2015. The LUH2 dataset includes a new wood harvest reconstruction, new representation of shifting cultivation, crop rotations, and management information including irrigation and fertiliser application. The model datasets do not yet include the FAO FRA 2020 update (FAO 2020b).

Higher emissions estimates are expected from DGVMs compared to bookkeeping estimates, because DGVMs include a loss of additional sink capacity of 3.3 ± 1.1 $GtCO_2$ yr^{-1} on average over 2009-2018, which is increasing over time (Friedlingstein et al. under review). This arises because the methodological setup requires a reference simulation without AFOLU activity, so DGVMs include the sink capacity forests would have developed in response to environmental changes on areas that in reality have been cleared (Pongratz et al., 2014; Gitz and Ciais 2003)(WGI Chapter 5). Understanding of the effect of land management changes on regional and global net AFOLU emissions has *low confidence* because of the lack of global estimates of flux from a wide range of practices that are often not included or not fully represented in models. For example: forest dynamics (Erb et al. 2013; Pugh et al. 2019; Le Noe et al. 2020) forest management including wood harvest (Arneth et al. 2017; Erb et al. 2018) agricultural and grassland practices (Pugh et al. 2015; Sanderman et al. 2017; Conant et al. 2017; Erb et al. 2018; Pongratz et al. 2018; Bai et al. 2019); fire suppression (Andela et al. 2017; Arora and Melton 2018); erosion of soil carbon and buried in river sediments or the open ocean (Regnier et al. 2013; Wang et al. 2017); aerosol-induced cooling (Zhang et al. 2019); the effects of drought (Humphrey et al. 2018; Green et al. 2019; Kolus et al. 2019); while observations from leaf to global scale suggest higher than expected CO_2 fertilisation (Haverd et al. 2020). These omissions can lead to over- or under-estimates and misallocation between anthropogenic and natural fluxes (Erb et al. 2018; Henttonen et al. 2019; Bastos et al. 2020).

Carbon emissions from peat burning have been estimated based on the Global Fire Emission Database (GFED4s; van der Werf et al., 2017). These were included in the bookkeeping model estimates and and added 2.0 GtC over 1960-2019. Peat drainage accounted for an additional 8.6 GtC 1960-2019 from for croplands and grasslands according to FAO (http://www.fao.org/faostat/en) (as used by the models Hansis et al., 2015 and Gasser et al., 2020) compared to 5.4 GtC for Hooijer et al. (2010) for Indonesia and Malaysia (a used by Houghton and Nasikas, 2017). Note that CO_2 emissions from biomass burning are generally treated as carbon neutral in NGHGIs (IPCC 2006; 2019b) if the vegetation regrows.

AFOLU CO_2 emission and trends for the pre-industrial and Industrial Era are assessed in WGI Chapter 5. Cumulative carbon losses since the start of agriculture and forestry have been estimated at 116 PgC for soils (Sanderman et al. 2017), and 447 PgC (375–525 PgC) for vegetation (Erb et al. 2018).

7.2.2.2 *Global gross AFOLU fluxes*

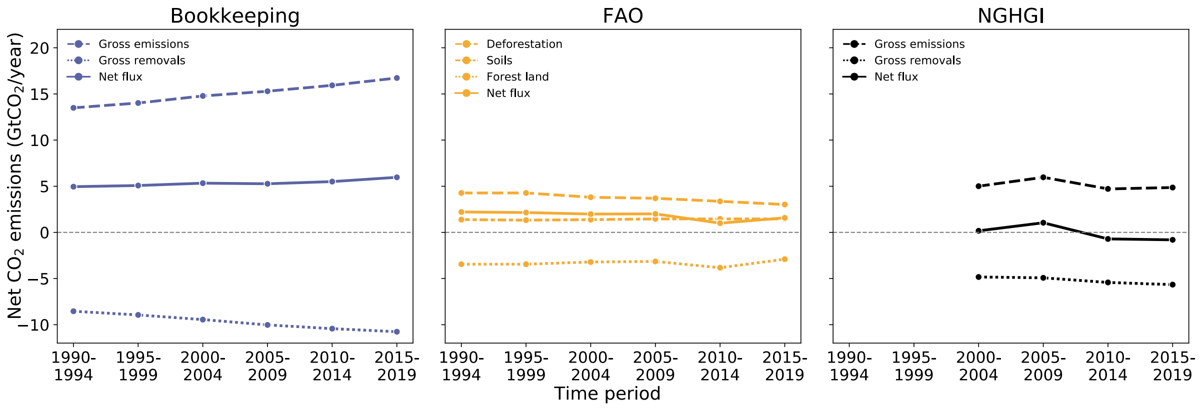

Figure 7.5 Global gross fluxes of CO_2 due to AFOLU (5-yearly averages from 1990 – 2019, $GtCO_2\ yr^{-1}$). Positive numbers represent emissions. Left panel: estimates based on the average of three bookkeeping models (BLUE – Hansis et al. 2015; H&N – Houghton and Nassikas 2017; OSCAR – Gasser et al. 2020), showing the gross emissions (dashed line), the gross removals (dotted line) and net flux (solid line). These include land cover change (e.g. deforestation, afforestation), forest management including wood harvest and regrowth, grassland management, agricultural management, peat burning and draining. Middle panel: data downloaded from FAOSTAT (http://www.fao.org/faostat/ - downloaded: November 2020), showing the net emissions from deforestation (dashed line), net emissions from organic soils, this includes peatland drainage and burning (dash-dotted line), net emissions from forest land, this includes managed forest land which primarily acts as a sink of CO_2 (dotted line) (Tubiello et al., 2020) and the Net flux (solid line). Right panel: estimates from National Greenhouse Gas Inventories (NGHGI) based on country reports to the UNFCCC for LULUCF (Grassi et al. 2020), showing the gross emissions (dashed line), the gross removals (dotted line) and the Net flux (solid line).

The net AFOLU flux consists of gross emissions (e.g. loss of biomass and soil carbon in clearing natural vegetation including decay of dead material, degradation, logging, harvested product decay, emissions from peat drainage and burning) and gross removals (e.g. CO_2 uptake in planted or re-growing vegetation after harvest or agricultural abandonment, accumulation of harvested wood products) (Figure 7.5). There is *high certainty* that AFOLU activities have resulted in large gross emissions and removals of CO_2 over recent decades although there is *medium certainty* in the size of these gross fluxes due to different methodological approaches and inclusion of different processes and scales.

For the bookkeeping models, gross emissions are on average 2-3 times larger than net emissions, increasing from an average of 12.8 ± 4.4 $GtCO_2\ yr^{-1}$ for the decade of the 1960s to an average of 16.1 ± 5.9 $GtCO_2\ yr^{-1}$ during 2010-2019 (Friedlingstein et al. under review). They are higher for the two models (Hansis et al. 2915; Gasser et al. 2020) that include shifting cultivation. Gross emissions are not available for the DGVMs. For NGHGIs, gross CO_2 emissions are mainly from deforestation and peat fires and decomposition, while removals are mainly from forest land (Grassi et al. 2020). Other fluxes (from cropland, grassland, wetland) can be either emissions or removals, depending on the country, but globally they are close to zero. There was little change in the NGHGI gross emissions (4.9 $GtCO_2\ yr^{-1}$ in 2015), but an increase in removals from 4.8 $GtCO_2\ yr^{-1}$ in 2000 to 5.7 $GtCO_2\ yr^{-1}$ in 2015.

The FAO net flux is the balance of (i) deforestation fluxes (3.1 $GtCO_2\ yr^{-1}$) during 2010-2019, with 90% of the total in non-Annex I countries (Tubiello et al. 2020), (ii) the net of emissions and removals from "forest land" (-3.3 $GtCO_2\ yr^{-1}$), a large net sink roughly equally divided between Annex I and non-Annex I countries (Tubiello et al. under review), and (iii) a net source of 1.4 $GtCO_2\ yr^{-1}$ from soils including peatland draining (FAO 2020c). Estimates indicate significant reduction of deforestation emissions during 1990-2000 from 4.3 to 2.9 $GtCO_2$ yr^{-1} during 2016-2020 (around 30%). The forest land removals overall decreased from 3.4 $GtCO_2$ yr^{-1} in 1991 to 2000 to -2.6 $GtCO_2$ yr^{-1} in 2016 to 2020 (around 20%). Thus, fluxes involving forests alone changed from a small net source to a small net sink. Emissions from peatland soils also decreased from 1.4 $GtCO_2$ yr^{-1} in 1990 to 1999, to 1.4 $GtCO_2$ yr^{-1} in 2010-2019.

7.2.2.3 Regional AFOLU CO_2 flux

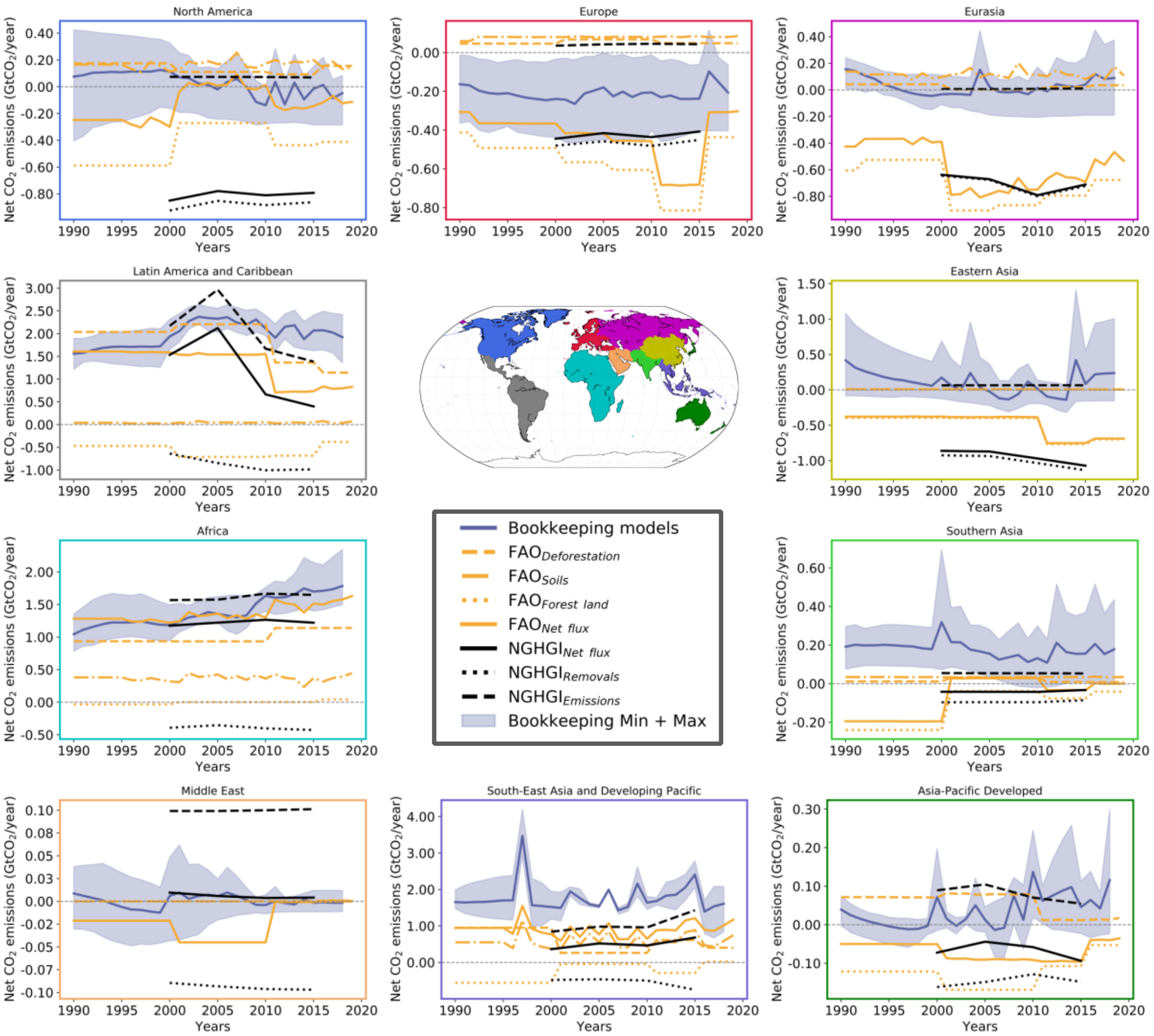

Figure 7.6 Regional gross and net flux of CO_2 due to AFOLU estimated using different methods for the period 1990 - 2019 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. The upper-central panel depicts the world map shaded according to the IPCC AR6 regions corresponding to the individual graphs. In each regional panel - Purple line: the mean estimate and minimum and maximum (purple shading) from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). Yellow line: data downloaded from the FAOSTAT (http://www.fao.org/faostat/ - downloaded: November 2020). Respective lines show the net emissions from deforestation (dashed line), net emissions from organic soils, this includes peatland drainage and burning (dash-dotted line), net emissions from forest land, this includes managed forest land which primarily acts as a sink of CO_2 (dotted line) (Tubiello et al. 2020) and the total Net flux (solid line). Black line: Net emissions estimates from National Greenhouse Gas Inventories (NGHGI) based on country reports to the UNFCCC for LULUCF (Grassi et al. in review), showing the gross emissions (dashed line), the gross removals (dotted

line) and the Net flux (solid line). Note: all regional figures have a different range in the Y-axis, the grey-line at 0 $GtCO_2$ yr^{-1} has been added as guide for the reader. [note regional gross fluxes were not available from the bookkeeping models for this draft, but will be included in the final draft]

Overall, there is *high confidence* of large gross emissions due to deforestation in Latin America, Africa and South-East Asia from 1990 to 2019, with a decrease in Latin America, an increase in Africa and a less certain trend in South-East Asia over this period (Figure 7.6). There is *high confidence* of large gross sinks across several regions due to forest regrowth and sinks in managed forests. There is *high confidence* of net AFOLU CO_2 sink in Europe, and *medium confidence* of a net sink in North America and Eurasia since 2010, while most other regions are net sources (*high confidence*).

Deforestation gross emissions estimated by FAO (Tubiello et al. 2020) were highest in 2000-2019 in Latin America (1.3 $GtCO_2$ yr^{-1}) where they decreased since 1990, in Africa (1.1 $GtCO_2$ yr^{-1}) where they increased, and in South-East Asia (0.5 $GtCO_2$ yr^{-1}) where they decreased. NGHGI gross emissions in 2015 were also highest in Africa (1.6 $GtCO_2$ yr^{-1}) and also showed an increase, while emissions decreased from 2.2 to 1.4 $GtCO_2$ yr^{-1} in Latin America but increased from 0.8 $GtCO_2$ yr^{-1} to 1.4 $GtCO_2$ yr^{-1} in South East Asia (Grassi et al. 2020). The bookkeeping models also showed the highest net flux in these three regions largely driven by deforestation (Friedlingstein et al. under review).

The forest sink estimated by FAO was nearly equally split between Eastern Asia, Eurasia, Europe, Latin America and North America and South East Asia, and a small net source from Africa since year 2000 due to forest degradation (loss of carbon stock). The Russian Federation, USA, China, Indonesia and India, all had large sinks and an increasing sink rate (Tubiello et al., submitted). The NGHGIs also showed large gross sinks in the same regions as FAO, but with much larger gross sink in North America and Eastern Asia, and a gross sink rather than small source from forest lands in Africa.

FAO net emissions from soils were largely driven by peatland draining, mostly in Africa (0.4 $GtCO_2$ yr^{-1}), and South East Asia (0.6 $GtCO_2$ yr^{-1}) and North America (0.2 $GtCO_2$ yr^{-1}) and Eurasia (0.1 $GtCO_2$ yr^{-1}) (FAO 2020c). The bookkeeping models also include CO_2 flux due to peatland burning (e.g causing the peak in South -East Asia in 1998) and draining.

Since the turn of the century there have been an increasing number of studies using remote-sensing technology that confirm gross CO_2 emissions from tropical deforestation, forest degradation and peatland-conversion, and gross CO_2 removals from intact and regrowth forests. During 2000-2017 net estimated net emissions varied from 0.84 $GtCO_2$ yr^{-1} to 10.34 $GtCO_2$ yr^{-1} (Table 7.2). Differences can in part be explained by spatial resolution, the definition of "forest", and more importantly the inclusion of processes such as degradation and growth in intact and secondary forests. Most of the studies in Table 7.2 do not consider soil fluxes. Emissions from peat soils across the tropics between 2001 to 2012 have been estimated as 1.21 $GtCO_2$ yr^{-1} (Busch and Engelmann 2017) and 1.93 $GtCO_2$ yr^{-1} (Grace et al. 2014). Remote sensing studies report committed emissions; i.e. all of the carbon lost is assumed to be released to the atmosphere in the year of deforestation.

Remote sensing products that specifically monitor carbon dynamics over longer periods of time can capture temporal and spatial dynamics, such as the impact of disturbances on carbon recovery. This can help to attribute changes to anthropogenic activity or natural inter-annual climate variability (Fan et al. 2011). For example, Fan et al. (2019) found that aboveground carbon peaked in 2011 in tropical America, suggesting that the vegetation recovered following the 2010 drought. A follow up study found that after the 2015-2016 El Niño event, tropical humid forests in America and Africa did not recover to prior carbon stocks (Wigneron et al. 2020). Newer satellite products with higher spatial resolution makes it easier to determine carbon dynamics in regrowth forests, which are expected to play a key role as climate mitigation solutions to the Paris Agreement (Grassi et al. 2017). Recent increases in Amazonian deforestation resulted in gross emissions equal to 0.6 $GtCO_2$ yr^{-1} (PRODES, no date; Aragão et al. 2018), of which secondary forest regrowth in the Brazilian Amazon offset 9 to 14% (Smith et al. 2020; Heinrich et al. under review). Yet disturbances such as fire and repeated deforestations, were found to reduce the regrowth rates of secondary forests by 8 to 55% depending on the region of regrowth (Heinrich et al. under review).

Table 7.2 Satellite based estimates of the net flux in tropical forests. Positive value represents emissions; negative value represents removals.

Study	Gross Tropical forest emissions ($GtCO_2yr^{-1}$)	Gross Tropical forest removals ($GtCO_2yr^{-1}$)	Net Tropical flux ($GtCO_2yr^{-1}$)	Period covered	Processes included	Product resolution
(Harris et al. 2012)	2.97	-	-	2000 - 2005	Deforestation	1km x 1km
(Achard et al. 2014)	3.23	-0.36	2.87	2000 - 2010	Deforestation	< 1km x 1km
(Tyukavina et al. 2015)	3.75 (4.78)	-	-	2000 – 2012	Deforestation, degradation (includes Belowground carbon)	30m x 30m
(Pan et al. 2011)	10.34	-10.05	0.29	2000 -2007	Deforestation, degradation, soils, intact and regrowth forests	Mix of inventory data remote sensing and models
(Busch and Engelmann 2017)	3.9 (1.21 from peat soils)	-	-	2001 – 2012	Deforestation and peatland emissions	30m x 30m
(Zarin et al. 2016)	2.27	-	-	2001 – 2013	Deforestation	30m x 30m
(Liu et al. 2015)	-	-	0.84 (1.9)	2003 – 2012	Deforestation (+ below-ground)	25km x 25km
(Baccini et al. 2017)	3.16	-1.56	1.6	2003 – 2014	Deforestation, degradation, management, disturbance and recovery	30m x 30m
(Grace et al. 2014)	7.37	-6.78	0.58	2005 - 2010	Deforestation, degradation, harvest, plantation, peat burning, secondary forests and forest growth)	Derived from previous remote sensing studies
(Fan et al. 2019)	10.49 (2.86*) (7.63**)	-10.89 (-2.53***) (-8.36****)	-0.4	2010 - 2017	*Deforestation, **degradation and disturbances, regrowth***, and intact forest****	25km x 25km

7.2.2.4 Natural response of land to environmental change and the net land-atmosphere flux CO_2

In addition to the direct anthropogenic AFOLU fluxes, there is a non-anthropogenic land sink that provides a natural sink service in removing anthropogenic CO_2 emissions (*high confidence*) and may be affected by future AFOLU activity or climate change. It is predominantly due to the natural response of land to human-induced environmental change (e.g. climate change, and the fertilising effects of increased atmospheric CO_2 concentration and nitrogen deposition), the "indirect anthropogenic effects" (IPCC 2010). DGVM models estimate the effects of environmental change on unmanaged and managed lands provided a net flux of -12.5 ± 3.2 $GtCO_2$ yr^{-1} during 2009-2018, a sink of around 31% of global anthropogenic emissions of CO_2 (*medium confidence*) (Friedlingstein et al. under review). There are large interannual variations of up to 7.3 $GtCO_2$ yr_{-1}, generally showing a decreased land sink during El Nino events. The land sink is estimated directly by DGVMs consistent with the SRCCL; calculating it as the residual of other carbon budget fluxes as in AR5 gives similar results (Freidlingstein et al. under review). The natural land sink has increased since 1900 and has slowed the rise in global land-surface air temperature by 0.09 ± 0.02°C since 1982 (*medium confidence*) (Zeng et al. 2017). Data from forest inventories around the world corroborate a modelled land sink (Pan et al. 2011). The Carbon Budget is discussed in more detail in WGI Chapter 5 and impacts of climate change on vegetation and soils in WGII, Chapter 2 and 5.

When combining the anthropogenic AFOLU net source with the non-AFOLU net sink, the total net land-atmosphere flux was -7.0 ± 4.0 $GtCO_2$ yr^{-1} (net sink) during 2009-2018, (*high confidence* in net sink*, medium confidence* in magnitude) (Friedlingstein et al. under review). Worldwide atmospheric measurements of CO_2 corroborate that the entire land surface (land-atmosphere flux) is a net sink due to a combination of all natural and anthropogenic processes (*high confidence*). Inversion models using atmospheric observations give a global range for 2010 to 2019 from -4.4 to -8.4 $GtCO_2$ yr^{-1}. (Van Der Laan-Luijkx et al. 2017; Rödenbeck et al. 2003; 2018; Chevallier et al. 2005; Feng et al. 2016; Niwa et al. 2017; Patra et al. 2018). Inversion models cannot separate anthropogenic and natural biospheric fluxes globally, but they can identify regional hot-spots and the underlying causes (Bastos et al. 2020).

7.2.2.5 Implications of differences in AFOLU CO_2 fluxes between global models and National Greenhouse Gas Inventories (NGHGIs), and reconciliation

Cause of the different fluxes between global models and countries

The ~5 $GtCO_2$ yr^{-1} difference in the anthropogenic FOLU estimates between global models and national greenhouse gas inventories (NGHGIs; see Figure 7.4) is largely the results of a greater CO_2 sink estimated by countries (Grassi et al. 2020), mostly occurring in forests, and is potentially a consequence of: (i) simplified and/or incomplete representations of management in global models (Popp et al. 2017 Pongratz et al. 2018), in particular the role of forest management in promoting biomass expansions and thickening (Kauppi et al. 2020); (ii) inaccurate and/or incomplete estimation of LULUCF fluxes in NGHGIs (Grassi et al. 2017), especially in developing countries, primarily in non-forest land uses and in soils, and (iii) conceptual differences in how global models and NGHGIs define 'anthropogenic' CO_2 flux from land (Grassi et al. 2018). The impacts of (i) and (ii) are difficult to quantify, and result in uncertainties that will decrease slowly over time through improvements of both models and NGHGIs. By contrast, the inconsistencies in (iii) and its resulting biases can be assessed and addressed, as explained below.

Due to differences in purpose and scope, the largely independent scientific communities supporting the global land flux modelling (bookkeeping models; Integrated Assessment Models, IAMs; and Dynamic Global vegetation Models, DGVMs) and the compilation of NGHGIs have developed different approaches - valid in their own specific contexts - to identify anthropogenic CO_2 fluxes for the land sector, especially for forest (Grassi et al. 2018; IPCC SRCCL). As summarised in Figure 7.7a, the different approaches relate to the attribution of the processes responsible for land fluxes and to the forest area that is considered managed.

The processes responsible for fluxes from land have been divided into three categories (IPCC 2006; 2010): (1) the *direct effects* of anthropogenic activity due to changing land cover and land management; (2) the *indirect effects* of anthropogenic environmental change, such as climate change, carbon dioxide (CO_2) fertilisation, nitrogen deposition; and (3) *natural effects,* including climate variability and a background natural disturbance regime (e.g. wildfires, windthrows, diseases).

Global models estimate the anthropogenic land CO_2 flux considering only the impact of most of the direct human induced effects on a comparatively small area of managed forest. The DGVMs estimate also the non-anthropogenic land CO_2 flux (Land sink) that results from indirect human-induced effects and of 'natural effects' in both managed and unmanaged lands. In contrast, estimates of the anthropogenic land CO_2 flux in NGHGIs (LULUCF) include the impact of direct effects, and in most cases of indirect effects, from a much bigger area of managed forests than those used by global models (Figure 7.7a).

The approach used by countries follows the methodological guidance provided by the IPCC for estimating NGHGIs (IPCC 2006, 2019). Separating anthropogenic from non-anthropogenic effects on the land CO_2 sink is impossible with direct observation (IPCC, 2010). Since most NGHGIs are fully or partly based on direct observations, such as national forest inventories, the IPCC adopted the 'managed land' concept as a pragmatic proxy to facilitate NGHGI reporting. Anthropogenic land GHG fluxes (direct and indirect effects) are defined as all those occurring on managed land, that is, where human interventions and practices have been applied to perform production, ecological or social functions (IPCC 2006, 2019). GHG fluxes from unmanaged land are not reported in NGHGIs because they are assumed to be non-anthropogenic. The definition of managed land used in NGHGIs is typically broad, e.g. it may include parks and protection forests, while global models include only those areas that were subject to intense and direct management such as clear-cut harvest.

Reconciliation of the differences between global models and countries

Reconciling the differences in FOLU CO_2 emissions between global models and NGHGIs is important to build confidence in land-related CO_2 estimates and to assess country progress in the context of the Global Stocktake. To make the global model results and NGHGIs comparable one can either adapt the NGHGIs' approach to the approach of global models, or vice versa. Since changing the NGHGIs' approach - based on several UNFCCC decisions - is impractical, a method to translate and adjust the output of global models has been proposed and successfully implemented for reconciling most of the difference between a bookkeeping model and NGHGIs (Grassi et al. 2018). More recently, an improved version of this approach has been applied to the future mitigation pathways estimated by IAMs (Grassi et al. 2020), for which the implications for the Global Stocktake are discussed in Cross-Chapter Box 5. This method implies a post-processing of current global models' results that addresses the two components of the discrepancy described above: (i) how the impact of human-induced environmental changes (indirect effects) are considered, and (ii) the extent of forest considered 'managed'. Essentially, this approach adds DGVM estimates of CO_2 fluxes due to indirect effects from non-intact forest area (taken as proxy of countries' managed forest) to the original global models' anthropogenic land CO_2 fluxes (see Figure 7.7b).

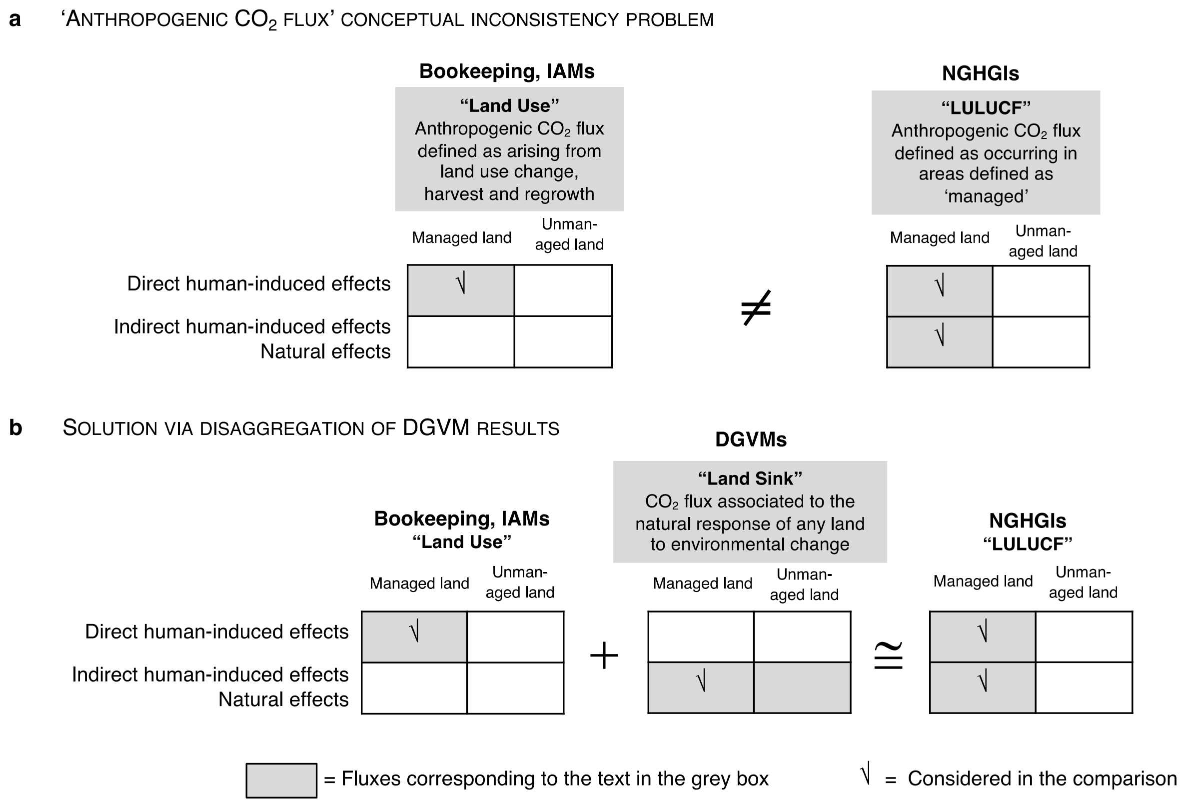

Figure 7.7 Main conceptual inconsistencies between global models (bookkeeping models, IAMs and DGVMs) and NGHGIs definitions of what is considered the 'anthropogenic' land CO_2 flux, and proposed solution (from Grassi et al. 2020). a, Differences in defining the anthropogenic land CO_2 flux by global models ('Land use') and NGHGIs ('LULUCF'), including the attribution of

processes responsible for land fluxes (as defined by IPCC 2006, 2010) in managed and unmanaged lands. The anthropogenic land CO_2 flux by global models typically includes only the CO_2 flux due to 'direct human-induced effects' (land-use change, harvest, regrowth). By contrast, NGHGIs consider anthropogenic all fluxes occurring in areas defined as 'managed', typically including also most of the sink due to 'indirect human-induced effects' (climate change, atmospheric CO_2 increase, N deposition etc.) and due to 'natural effects' (climate variability, background natural disturbance regime). In addition, countries consider 'managed' a much greater area (≈ 3 Billion ha globally) than global models (typically 0.5-1.5 Billion ha). Due to these differences, land CO_2 fluxes from global models are not comparable to those from NGHGIs (IPCC SR 1.5C, IPCC SR CCL). b, Proposed solution to the inconsistency, via disaggregation of the 'Lank sink' flux from DGVMs (from indirect human-induced and natural effects) into CO_2 fluxes occurring in managed and in unmanaged lands. This requires that the area of managed land over which the Land sink is estimated is comparable to the one in NGHGIs, especially for the area of managed forest (where most of LULUCF CO_2 flux of NGHGIs comes from). Since maps of managed forest are usually not available in country reports, Grassi et al. 2020 used the non-intact forest (areas within the current forest landscapes extent characterised by remotely-detected signs of human activity, derived from Potatov et al. 2017) as proxy for managed forest in NGHGIs. The sum of 'Land-use' flux (direct effects from global models) and the 'Land sink' flux from 'non-intact forest' (indirect effects from DGVMs) produces an adjusted global model' CO_2 flux which is conceptually more comparable with LULUCF fluxes from NGHGIs. Note that the figure may in some case be an oversimplification, e.g. not all NGHGIs necessarily include all recent indirect effects.

Cross-Chapter Box 5

Implications of reconciled anthropogenic CO_2 fluxes for assessing collective climate progress

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The Global Stocktake aims to assess the countries' collective progress towards the long-term goals of the Paris Agreement in the light of the best available science. Historical progress is assessed based on NGHGIs, while expectations of future progress are based on country climate targets (e.g., NDCs for 2025 or 2030 and long-term strategies for 2050). Scenarios consistent with limiting warming well-below 2°C and 1.5°C developed by IAMs (see IPCC SR 1.5C) will likely play a key role as benchmarks against which countries' aggregated future mitigation pledges will be assessed. This, however, requires that estimates used to derive the emission pathways and country data used to measure progress are comparable.

Following the pragmatic solution described in Section 7.2.2.5, Grassi et al. (2020) show how reallocating part of the land sink from the 'non-anthropogenic' to the 'anthropogenic' component helps to reconcile the ~5 $GtCO_2$ yr^{-1} difference between anthropogenic land CO_2 estimates of IAMs and NGHGIs at both global and regional level. This approach and its implications when comparing climate targets with global mitigation pathways are illustrated in, Figure 1a-f, within this Box.

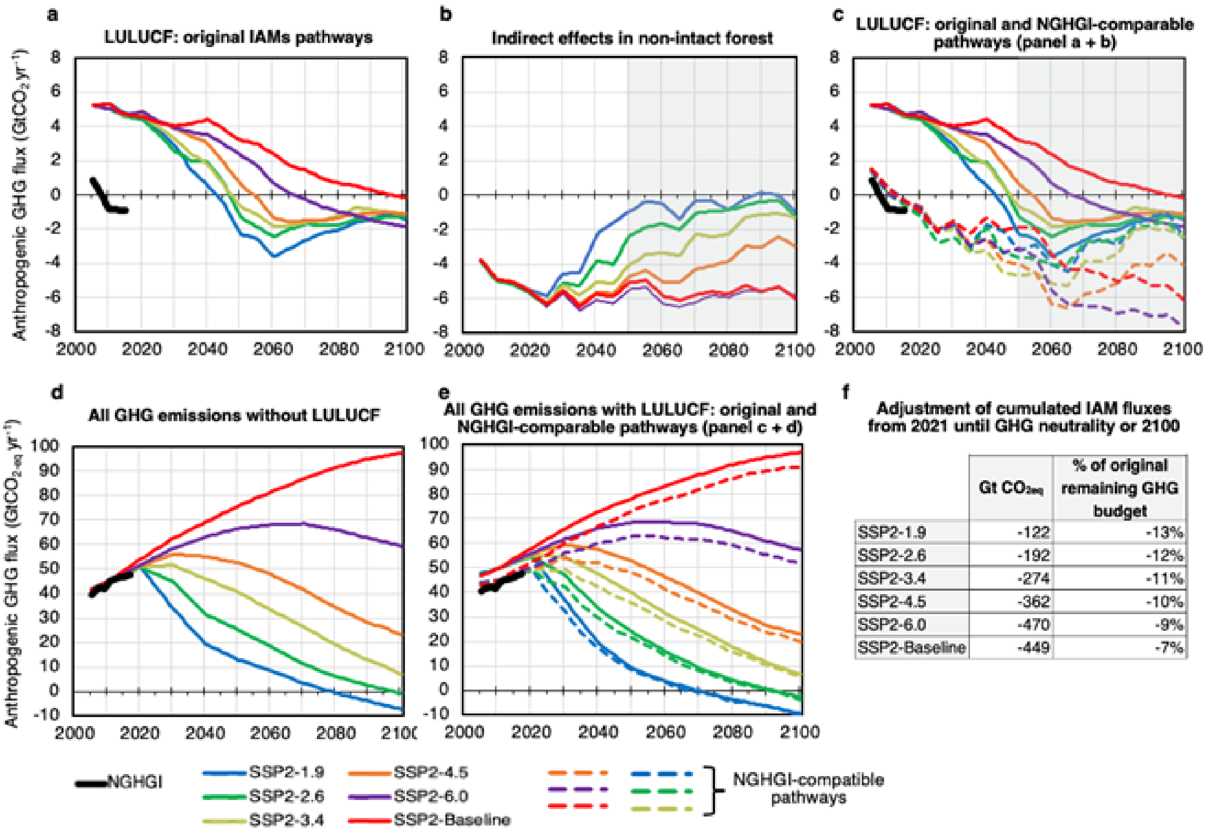
By adjusting the original IAM output (Figure. 7.32a) with the indirect effects from non-intact forests (Fig. 7.32b, estimated by DGVMs) NGHGI-comparable pathways can be derived (Figure. 7.32c). These changes do not directly affect non-LULUCF emissions, which do not require adjustments (Figure. 7.32d). However, since the atmosphere does not distinguish where CO_2 emissions originate from (i.e., whether from LULUCF or from fossil fuels), the proposed land-related adjustments indirectly influence also the NGHGI- comparable economy-wide GHG pathways (Cross-Chapter Box 5, Figure 1e).

Because future forest sink behaviour is highly uncertain, the proposed adjustment suggests additional uncertainty in NGHGI- comparable benchmarks. Currently, the future forest sink – and its uncertainty – is taken into account via the use of simple carbon-cycle and climate models (see WGI Cross-Chapter Box 7.1), like MAGICC (Meinshausen et al. 2011), which is used for (or within) all main IAMs to evaluate whether a certain mitigation pathway is consistent with a specified climate target. The uncertainty in future forest sink is therefore always included independently of whether these flows are labelled as anthropogenic (as countries do) or natural (as global models do).

This approach does not imply that the original decarbonisation pathways should be modified, nor does it suggest that indirect effects should be considered in the mitigation efforts. It simply ensures that an appropriate like-with-like comparison is made: if countries' climate targets use the NGHGI definition of anthropogenic emissions, and thus include a greater forest sink due to indirect effects, this same definition should be applied to derive NGHGI-comparable future emissions benchmarks and remaining GHG budget (i.e. the allowable emissions until net zero GHG emissions consistent with a certain climate target). For example, for SSP2-1.9 and SSP2-2.6 (representing pathways in line with 1.5°C and well-below 2°C limits under SSP2 assumptions), this NGHGI-comparable remaining GHG budget is lower by 122-192 $GtCO_{2-eq}$ than the original remaining GHG budget according to the models' approach (panel j). This difference is attributed entirely to differences in the estimate of CO_2 emissions. Similarly, the remaining GHG budgets published by the IPCC can only be used in combination with the definition of anthropogenic emissions as used by the IAMs. Where countries did not appropriately account for this definitional mismatch when setting their targets, correcting for this will result in a perceived increase of the required collective mitigation effort. The same applies in the context of net zero GHG (or carbon) targets, which also depend on the definition of 'anthropogenic' emissions and removals.

The above also means that if country climate targets using the NGHGI definition are used together with IAM pathways to assess collective climate progress, adjustments have to be made. The assessment of the global 2030 'emission gap' between aggregated country NDCs and specific target mitigation pathways – as published annually by UNEP – is only affected to a limited degree. This is because some estimates of global emissions under the NDCs already use the same land-use definitions as the IAM mitigation pathways (Rogelj et al. 2017), and because historical data of global NDC estimates is typically harmonised to the historical data of global mitigation pathway projections (Rogelj et al. 2011). This latter procedure, however, is agnostic to the reasons for the observed mismatch, and often uses a constant offset. The adjustment proposed here allows to resolve this mismatch drawing on an understanding of the underlying reasons, and thus provides a more informed and accurate basis for estimating the emission gap.

In conclusion, the NGHGI-comparable emission pathways presented here – that can be further refined with improved estimates of the future forest sink – will enable a more accurate assessment of the progress achieved and of the adequacy of countries' mitigation pledges under the Paris Agreement.



Cross-Chapter Box 5, Figure 1 Impact of adjusting the IAMs' land CO_2 fluxes to the NGHGIs approach on global mitigation pathways (from Grassi et al. 2020). a-b, Global anthropogenic CO_2 fluxes from SSP2 scenarios: original IAM mitigation pathways and NGHGIs for LULUCF (a), fluxes due to indirect effects from non-intact forests (b, i.e. those fluxes generally considered 'anthropogenic' by countries but included in the 'natural land sink' by global models), and NGHGI-comparable LULUCF pathways (c, that is, original IAM results adjusted to the NGHGI approach by adding the indirect effects of panel b). The indirect effects in panel b decline over time with increasing mitigation ambition, mainly because of the weaker CO_2 fertilisation effect. In panel c, the dependency of the adjusted LULUCF pathways on the target becomes less evident after 2030, because the indirect effects in non-intact forest (which are progressively more uncertain with time, especially after 2050 as highlighted by the grey areas) compensate the effects of the original pathways. d-e, Global anthropogenic GHG emissions without LULUCF (d, where no adjustment is needed) and NGHGI-comparable pathways for global GHG emissions with LULUCF (e, obtained by combining panels c and d). NGHGI data are from PRIMAP HISTCR (Gütschow et al. 2019) for non-LULUCF (primarily based on country data reported to UNFCCC) and from Grassi et al. 2017 for LULUCF. h, Cumulative impact of the adjustments (i.e. cumulative indirect effects in non-intact forests) from 2021 until net zero GHG emissions or 2100 (whatever comes first) on the remaining GHG budget (i.e. the allowable emissions until net zero GHG emissions consistent with a certain climate target).

7.2.3 CH_4 and N_2O flux from agriculture, forestry and other land use

Trends in atmospheric CH_4 and N_2O concentrations and associated sources, including land and land use are discussed in Section 5.2.2 of the IPCC WGI sixth assessment report. Regarding AFOLU, the SRCCL and AR5 (Jia et al. 2019; Smith et al. 2014) identified three global non-CO_2 emissions data sources; EDGAR (Crippa et al. 2020), FAOSTAT (FAO 2019a; 2019b [all FAOSTAT values will be updated once new FAOSTAT data is finalised]) and the U.S. EPA (USEPA, 2019). Methodological differences have been previously discussed (Smith et al. 2014; Jia et al. 2019). It is important to note that in terms of AFOLU sectoral CH_4 and N_2O emissions, only FAOSTAT provides data on AFOLU emissions, while EDGAR and the USEPA consider just the agricultural component. Country GHG inventories (GHGIs) annually submitted to the UNFCCC (see Section 7.2.2.5) provide national AFOLU CH_4 and N_2O data, as included in the SRCCL (Jia et al. 2019). Aggregation of GHGIs to indicate global emissions must be with caution, as not all countries compile inventories, nor submit annually. Additionally, GHGIs may incorporate a range of methodologies (e.g. Thakuri et al. 2020; Ndung'u et al. 2018; van der Weerden et al. 2016), making comparison difficult. The analysis of complete AFOLU emissions presented here, is based on FAOSTAT data. For agricultural specific discussion, analysis considers EDGAR, FAOSTAT and USEPA data.

7.2.3.1 Global AFOLU CH_4 and N_2O emissions

Using FAOSTAT data, the SRCCL estimated average CH_4 emissions from AFOLU to be 160.8 ± 43 Mt CH_4 yr^{-1} for the period 2007-2016, with agriculture accounting for 88% of emissions (Jia et al. 2019). Latest data (FAO 2019a; 2019b) highlight a trend of growing AFOLU CH_4 emissions, with a 9% increase evident between 1990 and 2017, despite temporal trend variation. Forestry and other land use (FOLU) emission sources included biomass burning on forest land and combustion of organic soils (FAO 2019). Agriculture on average accounted for 87% of AFOLU emissions during the period. The SRCCL reported with *medium evidence* and *high agreement* that ruminants and rice production were most important contributors to overall growth trends in atmospheric CH_4 (Jia et al. 2019). Latest data confirm this in terms of agricultural emissions, with agreement between databases that agricultural CH_4 emissions continue to increase and that enteric fermentation and rice cultivation remain the main sources (Figure 7.8). The proportionally higher emissions from rice cultivation indicated by EDGAR data compared to the other databases, may result from the inclusion of Tier 2 methodology for this source within EDGAR (Janssens-Maenhout et al. 2019).

The SRCCL also noted a trend of increasing atmospheric N_2O concentrations, with *robust evidence* and *high agreement* that agriculture accounted for approximately two-thirds of overall global anthropogenic N_2O emissions. Average AFOLU N_2O emissions were reported to be 8.7 ± 2.5 Mt N_2O yr^{-1} for the period 2007-2016, of which agriculture accounted for 95% (Jia et al. 2019). A recent comprehensive review confirms agriculture as the principal driver of the growing atmospheric N_2O burden (Tian et al. 2020). Latest FAOSTAT data (FAO 2019a; 2019bJ5) document a 26% increase in AFOLU N_2O emissions between 1990 and 2017. In agreement with the SRCCL, agriculture on average accounted for 95% over that period. Agricultural soils were identified in the SRCCL and in recent literature as a dominant emission source, notably due to fertiliser application on croplands and manure production and deposition on pastures (Jia et al. 2019; Tian, 2020). There is agreement within latest data that agricultural soils remain the dominant source (Figure 7.8).

Aggregation of CH_4 and N_2O to CO_2 equivalence (using GWP_{100} IPCC AR6 values - see Box 2.2 and Annex B), suggests that AFOLU emissions increased by 13% between 1990 and 2017, though emissions showed temporal trend variability. Agriculture accounted for 89% of AFOLU emissions on average over the period, demonstrating more steady growth (FAO 2019a; 2019b). EDGAR (Crippa et al. 2020), FAOSTAT (FAO 2019a) and USEPA (USEPA 2019) data suggest aggregated agricultural emissions (CO_2-eq) to have increased since 1990, by 15 (1990-2018), 16 (1990-2017) and 19 (1990-2015) % respectively, with all databases identifying enteric fermentation and agricultural soils as the dominant agricultural emissions sources.

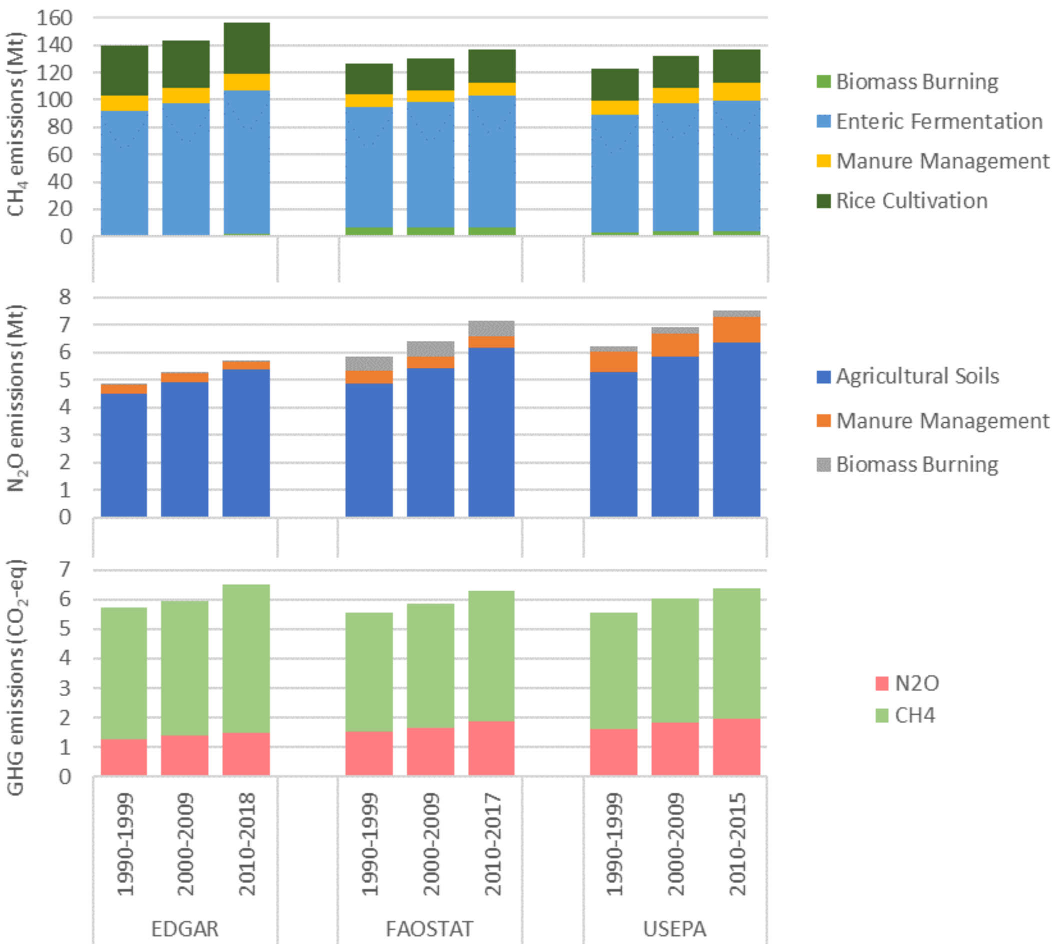


Figure 7.8 Estimated global mean agricultural CH_4 (Top), N_2O (Middle) and aggregated CH_4 and N_2O (using CO_2-eq according to GWP_{100} AR6 values) (Bottom) emissions for three decades according to EDGARv6.0 (Crippa et al. 2020), FAOSTAT (FAO 2019aJ4) and USEPA (USEPA 2019) databases [FAOSTAT values will be updated once new data is finalised]. **Latest versions of databases indicate historic emissions to 2018, 2017 and 2015 respectively, with average values for the post-2010 period calculated accordingly. For CH_4, emissions classified as 'Other Ag.' within USEPA data, are re-classified as 'Biomass Burning'. Despite CH_4 emissions from agricultural soils also being included, this category was deemed to principally concern biomass burning and classified accordingly. For N_2O, emissions classified within EDGAR as direct and indirect emissions from managed soils, and indirect emissions from manure management are combined under 'Agricultural Soils'. Emissions classified by FOASTAT as from manure deposition and application to soils, crop residues and synthetic fertilisers are combined under 'Agricultural Soils', while emissions reported as 'Other Ag.' under USEPA data are re-classified as 'Biomass Burning'.**

7.2.3.2 Regional AFOLU CH_4 and N_2O emissions

FAOSTAT data (FAO 2019aJ4; 2019bJ5) indicate Africa (+ 41%), followed by Southern Asia (+ 26%) to have the highest growth in AFOLU CH_4 emissions between 1990 and 2017 (Figure 7.9). Eurasia was characterised by notable emission reductions (- 52%), principally as a result of a sharp decline (- 61%) between 1990 and 1999. The average agricultural share of AFOLU emissions between 1990 and 2017 ranged from 66% in Africa to almost 100% in the Middle East.

Regarding agricultural CH_4 emissions and in agreement with AR5 (Smith et al. 2014), the SRCCL identified Asia as having the largest share (37%) from enteric fermentation and manure management since 2000, but Africa to have the fastest growth rate. These emissions were reported as declining in both Latin America and the Caribbean, and in Europe, while Asia was identified as responsible for 89% of rice cultivation emissions, which were reported as increasing (Jia et al. 2019). Considering classification by 10 regions, data suggest enteric fermentation to have dominated emissions in all regions since 1990, except in South-east Asia and Developing Pacific, where rice cultivation forms a principle source (FAO 2019aJ4; USEPA 2019). Databases indicate contrasting regional CH_4 emission trends due to methodological differences (see Section 7.2.3.1), making definitive conclusions difficult. However, all databases indicate considerable growth in Africa, both between 1990 and 2017, and during the last decade, where greatest regional increases in emissions from both enteric fermentation and rice cultivation were generally observed since 2010. Additionally, FAOSTAT data suggest that emissions from agricultural biomass burning account for a notably high proportion of agricultural CH_4 emissions in Africa (Figure 7.9).

Latest data suggest growth in AFOLU N_2O emissions in most regions between 1990 and 2017, with Southern Asia demonstrating highest growth (+ 72%) and Eurasia, greatest reductions (- 49%), the latter mainly a result of a 64% reduction between 1990 and 2000 (FAO 2019a; 2019b). Agriculture was the dominant emission source in all regions, its proportional average share between 1990 and 2017 ranging from 84% in South-eastern Asia and Developing Pacific, to almost 100% in the Middle East (Figure 7.9).

The SRCCL provided limited discussion on regional variation in agricultural N_2O emissions but reported with *medium confidence* that certain regions (North America, Europe, East & South Asia) were grazing land N_2O hotspots (Jia et al. 2019). AR5 identified Asia as the largest source and as having the highest growth rate of N_2O emissions from synthetic fertilisers between 2000 and 2010 (Smith et al. 2014). Latest data indicate agricultural N_2O emission increases in most regions, though variation between databases prevents definitive conclusions on trends, with Africa, South-east Asia and Developing Pacific, and Eastern Asia suggested to have had greatest growth since 1990 according to EDGAR (Crippa et al. 2020), FAOSTAT (FAO 2019a) and USEPA (USEPA 2019) data respectively. However, all databases indicate that emissions declined in Eurasia and Europe from 1990 levels, in accordance with specific environmental regulations put in place since the late 1980s (Tubiello 2019; Tian et al. 2020; European Environment Agency 2020), but generally suggest increases in both regions since 2010.

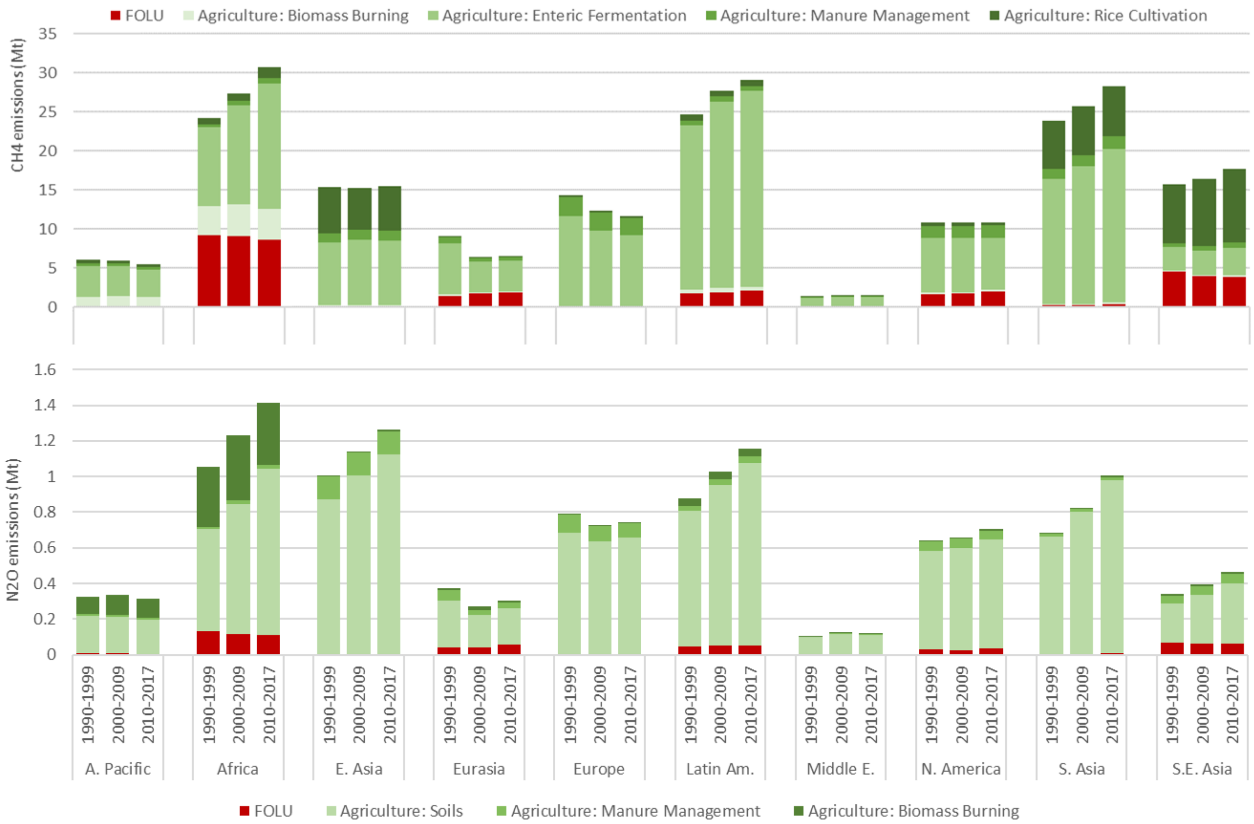


Figure 7.9 Estimated average AFOLU CH_4 (Top) and N_2O (Bottom) emissions for three decades according to FAOSTAT data by 10 global regions, with disaggregation of agricultural emissions (FAO 2019a; 2019b [values will be updated once new data is finalised]**). Latest FAOSTAT data provide historic emissions to 2017, and therefore average values for the post 2010 period are calculated accordingly. Note for N_2O, emissions from manure deposition and application to soils, crop residues and synthetic fertilisers are combined under 'Agricultural Soils'.**

7.2.4 Biophysical effects and short-lived climate forcers

Since the SRCCL, new evidence does not revise its conclusions, summarised here. Changes in land conditions from land cover change or land management jointly affect water, energy, and aerosol fluxes (biophysical fluxes) as well as GHG fluxes (biogeochemical fluxes) exchanged between the land and atmosphere (*high agreement, robust evidence*) (Erb et al. 2017; Arora and Montenegro 2011; O'Halloran et al. 2012; Naudts et al. 2016; Anderson et al. 2011). There is *high confidence* that changes in land condition do not just have local impacts but could also affect adjacent and more distant areas. Non-local impacts may occur in three different ways: GHG fluxes and subsequent changes in radiative transfer (Section 7.4), changes in atmospheric chemistry, thermal, moisture and surface pressure gradients creating horizontal transport (advection) (De Vrese et al. 2016; Davin and de Noblet 2010) and vertical transport (convection and subsidence) (Devaraju et al. 2018). Although regional and global biophysical impacts emerge from model simulations (De Vrese et al. 2016; Davin and de Noblet 2010; Devaraju et al. 2018), especially if the land condition has changed over large areas, there is *very low agreement* on the location, extent and characteristics of the non-local effects across models. There is *very low confidence* that the effects of such long-range processes can be experimentally confirmed.

Following changes in land conditions, CO_2, CH_4 and N_2O fluxes are quickly mixed into the atmosphere and dispersed, resulting in the biogeochemical effects being dominated by the biophysical effects at local scales (*high confidence*) (Li et al 2015; Alkame and Cescatti 2016). Forestation (Lejeune et al. 2018; Strandberg and Kjellström 2018), urbanisation (Li and Bou-Zeid 2013) and irrigation (Thiery et al. 2017; Mueller et al. 2015) modulate the likelihood, intensity, and duration of many extreme events including heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*) (Haberlie et al. 2014). There is *high confidence* that land conditions could be managed to mitigate GHG-induced climate change at local scale (Section 7.4). There is *high confidence and high agreement* that afforestation in the moist tropics (Perugini et al. 2017), irrigation (Mueller et al. 2015; Alther et al. 2015) and urban greening result in local cooling, *high agreement and medium confidence* on the impact of tree growth form (deciduous vs. evergreen) (Naudts et al. 2016; Luyssaert et al. 2018; Schwaab et al. 2020), and *low agreement* on the impact of wood harvest, fertilisation, tillage, crop harvest, residue management, grazing, mowing, and fire management on the local climate.

Studies of biophysical effects have increased since AR5 and confirmed the importance of accounting for biophysical effects including albedo (Betts 2000), turbulent fluxes (Bright et al. 2017) and emission of short-lived tracers (Kalliokoski 2020). However, most assessments are incomplete because observational and modelling studies omit one or several processes: responses of vegetation growth or distribution to climate change, impact of major disturbances such as droughts, nutrient dynamics, the dynamics of short-lived chemical tracers such as biogenic volatile organic compounds, and the effects of pollution such as atmospheric deposition, acidification, and ozone. Moreover, the study domain is often too small to document non-local effects. Consequently, the environmental conditions required to guarantee that specific changes in land conditions impact the local, regional and global climate as desired remain largely unknown.

7.3 Drivers

Since AR5, several global assessments (IPBES 2018; Shukla et al. 2019; UN Environment 2019; NYDF Assessment Report 2019; FAO 2020) and studies (e.g. Tubiello 2019; Tian et al. 2020) have reported on drivers affecting emissions and removals from AFOLU, and associated projections for the coming decades. The following analysis aligns with the drivers typology used by IPBES (2018) and the Global Environmental Outlook (UN Environment 2019). Drivers are divided into direct drivers resulting from human decisions and actions concerning land use and land-use change, and indirect drivers that operate by altering the level or rate of change of one or more direct drivers.

AR5 reported a decline in average annual aggregated AFOLU emissions between 1990-2010 but with opposite trends for Agriculture (crop and livestock production) and Forestry and Other Uses (FOLU). The marked decline of FOLU emissions over this period was mainly due to a slowdown in deforestation rates, while emissions from agriculture increased (Section 7.2). In recent decades, AFOLU emissions have resumed growth (Figure 7.3).

Although drivers of emissions in Agriculture and FOLU are presented separately in proceeding sections, they are interlinked, operating in many complex ways at different temporal and spatial scales, with outcomes depending on their interactions. For example, deforestation in tropical forests is a significant component of sectoral emissions. A review of deforestation drivers encompassing studies published between 1996 and 2013, indicated a wide range of variables associated with deforestation rates across many analyses and studies (Figure 7.10) (Busch and Ferretti-Gallon 2017). Higher agricultural prices were identified as a key driver of deforestation, while law enforcement, area protection, and ecosystem services payments were found to be important drivers of reduced deforestation.

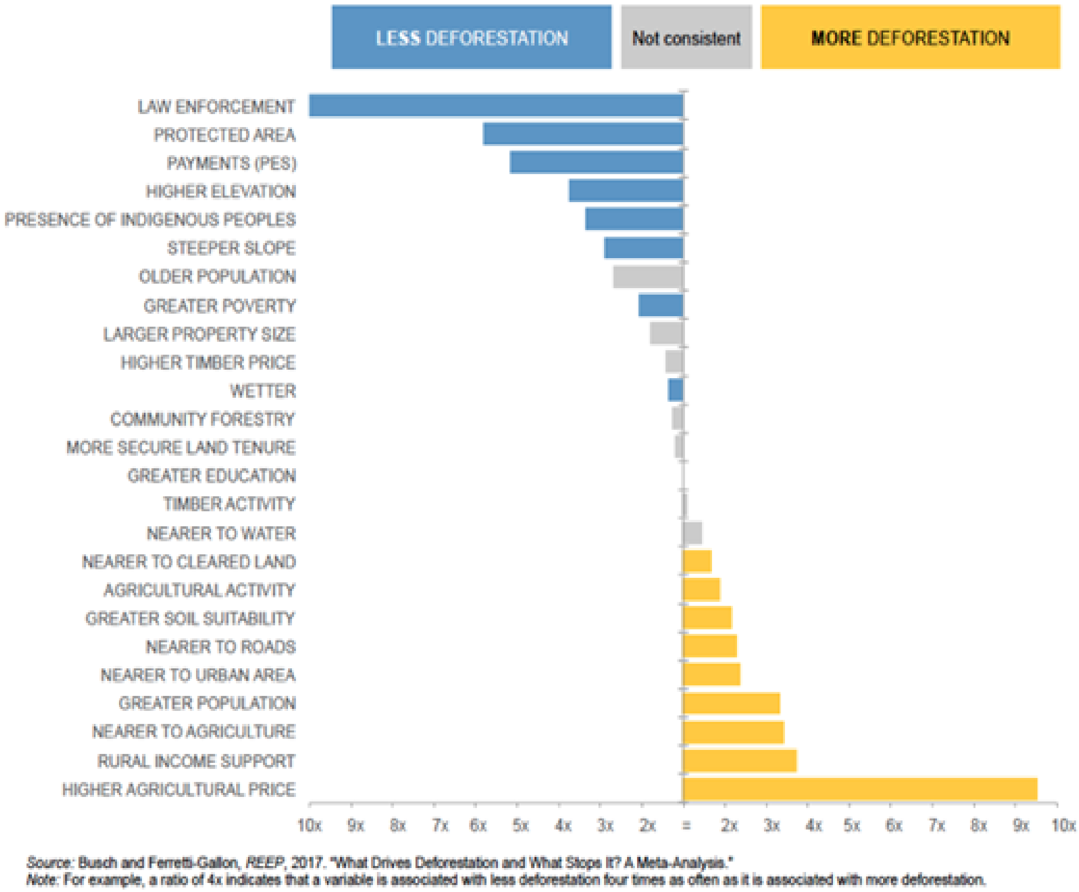


Figure 7.10 Association of driver variables with more or less deforestation (Busch and Ferretti-Gallon 2017).

7.3.1 Anthropogenic direct drivers – Deforestation, conversion of other ecosystems, and land degradation

The global forest area in 2020 is estimated at 4.1 billion ha, representing 31% of the total land area (FAO 2020). Most forests are situated in the tropics (45%), followed by boreal (27%), temperate (16%) and subtropical (11%) domains. Considering regional distribution of global forest area, Europe and the Russian Federation accounts for 25%, followed by South America (21%), North and Central America (19 %), Africa (16%), Asia (15%) and Oceania (5%). However, a significant share (54%) of the world's forest area concerns five countries – the Russian Federation, Brazil, Canada, the United States of America and China (FAO 2020). Forest loss rates differ among regions though the global trend is towards a net forest loss (UN Environment 2019). The global forest area declined by about 178 Mha in the 30 years from 1990 to 2020 (FAO 2020). The rate of net forest loss has decreased since 1990, a result of reduced deforestation in some countries and forest gains in others. The annual net loss of forest area declined from 7.8 Mha in 1990–2000, to 5.2 Mha in 2000–2010, to 4.7 Mha in 2010–2020, while the total growing stock in global forests increased (FAO 2020). The rate of decline in net forest loss during the last decade was due mainly to an increase in the rate of forest gain (i.e. afforestation and the natural expansion of forests). Some relevant direct drivers affecting emissions and removal in forests and other ecosystems are discussed in proceeding sections.

7.3.1.1 Conversion of natural ecosystem to agriculture

Previous IPCC reports identify land use change as an important driver of emissions and agriculture as a key driver of land use change, causing both deforestation and wetland drainage (Smith et al. 2014;

Smith et al. 2019). According to AR5, global agricultural land area increased by 7% between 1970 and 2010 but had decreased since 2000 (Smith et al. 2014). Latest data (FAO, 2020J1) indicate a slight reduction (- 2%) in total area between 2000 and 2018 (Figure 7.11), and changes in how agricultural land is used. During this period, the area devoted to permanent meadow and pasture decreased (- 5%) while cropland area increased (+ 3%). A key driver of this change has been a general trend of intensification, including in livestock production (UN Environment 2019; Barger et al. 2018; OECD-FAO 2019), whereby less grazing land is supporting increasing livestock numbers in conjunction with greater use of crops as livestock feed (Barger et al. 2018). The share of feed crops, such as maize and soybean, of global crop production is projected to grow as the demand for animal feed increases with further intensification of livestock production (OECD-FAO 2019). Despite increased demand for food, feed, fuel and fibre from a growing human population (FAO 2019), global agricultural land area is projected to remain relatively stable during the next decade, with increases in production expected to result from agricultural intensification (OECD-FAO 2019).

Despite a decline in global agricultural area, some regional expansion was evident between 2000 and 2018, notably in Latin America and the Caribbean (+ 5%) and Africa and the Middle East (+ 2%). The area of permanent meadow and pasture decreased in all regions apart from Latin America and the Caribbean where an increase was observed (+ 2%). Latin America and the Caribbean also recorded the greatest increase in cropland area (+ 20%) between 2000 and 2018, followed by Africa and the Middle East (+ 18%). Projections (OECD-FAO 2019) suggest continued expansion of both cropland and pasture in Latin America and the Caribbean during the next decade. Despite recent increases, agricultural area in Africa is projected to remain relatively stable over the next decade as net expansion is constrained by conflict, the smallholder structure prevalence, land degradation and alternative use (OECD-FAO 2019).

Mangroves form one of the most productive terrestrial ecosystems (Neogi 2020a). The global area of mangroves has experienced a significant decline (Thomas et al. 2017; Neogi 2020b), with a decrease of 1.0 Mha documented between 1990 and 2020 (FAO 2020). South Asia, Southeast Asia, and Asia-Pacific contain approximately 46% of the world's mangrove ecosystems and account for the highest global mangrove loss rates (Giri et al. 2011; Rivera-Monroy et al. 2017; Miettinen et al. 2019). The average annual rate of mangrove loss in Asia increased from 1,030 ha in 1990–2000, to 38,200 ha in 2010–2020 (FAO 2020). Primary drivers include conversion for agricultural use, notably oil palm plantations and rice cultivation and the expansion of aquaculture (e.g. shrimp farming) (Bhattarai and Giri 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Fauzi et al. 2019).

7.3.1.2 Infrastructure development and urbanisation

Although built-up areas occupy a relatively small fraction of land, since 1975 urban clusters (i.e. urban centres as well as surrounding suburbs) have expanded approximately 2.5 times, accounting for 7.6% of global land area (UN Environment 2019). Regional differences are striking. Between 1975 and 2015, built-up areas doubled in size in Europe while urban population remained relatively constant. In Africa built-up areas grew approximately fourfold, while urban population tripled (UN Environment 2019). Trends indicate that rural-to-urban migration will continue and accelerate in developing countries. This represents both a driver of increased environmental pressure but also an opportunity to enhance sustainability (e.g. by preserving or enhancing natural systems within cities for example lakes or natural and urban green infrastructures (UN Environment, 2019). If current population densities within cities remain stable, the extent of built-up areas in developed countries is expected to increase by 30% and triple in developing countries between 2000 and 2050 (Barger et al. 2018).

Urban expansion leads to landscape fragmentation and urban sprawl with effects on forest resources and land use (Ünal et al. 2019) while interacting with other drives. For example, in the Brazilian Amazon, the most rapid urban growth occurs within cities that are located near rural areas that produce commodities (minerals or crops) and are connected to export corridors (Richards and VanWey 2015).

Urbanisation, coastal development and industrialisation also play crucial roles in the significant loss of mangrove forests (Richards and Friess 2016; Rivera-Monroy et al. 2017; Hirales-Cota et al. 2010).

Among infrastructural developments, roads are one of the most consistent and most considerable factors in deforestation, particularly in tropical frontiers (Pfaff et al. 2007; Rudel et al. 2009; Ferretti-Gallon and Busch 2014). Projections of the International Energy Agency indicate that by 2050, another 25 million km of paved roads will be constructed globally. Nine-tenths of these roads will be located in developing nations, mostly in the tropics and subtropics, where the expansion of road networks increases access to remote forests that act as refuges for biodiversity and provide globally important ecosystem services (Campbell et al. 2017) (Box 7.1). Logging is one of the main drivers of road construction in tropical forests (Kleinschroth and Healey 2017). Besides the clearing associated with the construction of logging access roads, more severe impacts include increased fire incidence, soil erosion, landslides, and sediment accumulation in streams, wildlife poaching, illicit land colonisation, illegal logging and mining, land grabbing and land speculation (Laurance et al. 2009; Alamgir et al. 2017). Some roads, initially built for logging, become permanent, public roads with subsequent in-migration and conversion of forest to agriculture. Strategic landscape planning is necessary to design road networks that facilitate confined and efficient forest exploitation while preserving roadless areas.

Box 7.1 Case study: Reducing the impacts of roads on deforestation

Summary

Rapidly expanding roads, particularly in tropical regions, are linked to forest loss, degradation, and fragmentation. Also, poorly planned infrastructure can facilitate fires, illegal mining, and wildlife poaching with consequences for GHG emissions and biodiversity conservation. However, some initiatives are providing new approaches for better planning and then limit environmental and societal impacts**.**

Background

Although the number and extent of protected areas has increased markedly in recent decades (Watson et al. 2014), many other indicators reveal that nature is in broad retreat. For example, the total area of intact wilderness is declining rapidly worldwide (Watson et al. 2016), 70% of the world's forests are now less than 1 km from a forest edge (Haddad et al. 2015), the extent of tropical forest fragmentation is accelerating exponentially (Taubert et al. 2018). One of the most direct and immediate driver of deforestation and biodiversity decline is the dramatic expansion of roads and other transportation infrastructure (Laurance et al. 2014; Alamgir et al. 2017; Laurance and Burgues 2017).

Case description

From 2010 to 2050, the total length of paved roads is projected to increase by 25 million km (Dulac 2013) including large infrastructure-expansion schemes—such as China's One Belt One Road initiative (Laurance and Burgues 2017; Lechner et al. 2018) and the IIRSA program in South America (Laurance et al. 2001; Killeen 2007)—as well as widespread illegal or unplanned road building (Laurance et al. 2009; Barber et al. 2014). For example, in the Amazon, 95% of all deforestation occurs within 5.5 km of a road, and for every km of legal road there are nearly three km of illegal roads (Barber et al. 2014).

Interactions and limitations

More than any other proximate factor, the dramatic expansion of roads is determining the pace and patterns of habitat disruption and its impacts on biodiversity (Laurance et al. 2009; Laurance & Burgues 2017). Much road expansion is poorly planned. Environmental Impact Assessments (EIAs) for roads and other infrastructure are typically too short-term and superficial to detect rare species or assess long-term or indirect impacts of projects (Flyvberg 2009; Laurance and Burgues 2017). Another limitation is the consideration of each project in isolation from other existing or planned developments (Laurance et al. 2014). Hence, EIAs alone are inadequate for planning infrastructure projects and assessing their broader environmental, social, and financial impacts and risks (Laurance et al. 2015a; Alamgir et al. 2017, 2018).

Lessons

The use large-scale, proactive land-use planning is an option for managing the development of modern infrastructure. Approaches such as the "Global Roadmap" scheme (Laurance and Balmford 2013; Laurance et al. 2014) or Strategic Environmental Assessments (Fischer 2007) can be used to evaluate the relative costs and benefits of infrastructure projects, and to spatially prioritise land-uses to optimise human benefits while limited new infrastructure in areas of intact or critical habitats. For example, the Global Roadmap strategy has been used in parts of Southeast Asia (Sloan et al. 2018), Indochina (Balmford et al. 2016), and sub-Saharan Africa (Laurance et al. 2015b) to devise land-use zoning that can help optimise the many risks and rewards of planned infrastructure projects.

7.3.1.3 Extractive industry development

The extent and scale of mining is growing due to increased global demand (UN Environment 2019). Due to declining ore grades, more ore needs to be processed to meet demand, with extensive use of open cast mining. A low-carbon future will may be more mineral intensive with for example, clean energy technologies requiring greater inputs in comparison to fossil-fuel-based technologies (Hund et al. 2020). Mining presents cumulative environmental impacts, especially in intensively mined regions, including areas subject to hydraulic fracturing for oil (UN Environment 2019). The impact of mining on deforestation varies considerably across minerals and countries. Mining causes significant changes to the environment, for example through mining infrastructure establishment, urban expansion to support a growing workforce and development of mineral commodity supply chains (Sonter et al. 2015). The increasing consumption of gold in developing countries, increased prices, and uncertainty in financial markets is identified as driving gold mining and associated deforestation in the Amazon region (Alvarez-Berrios and Aide 2015; Dezécache et al. 2017; Asner and Tupayachi 2017; Caballero Espejo et al. 2018). The total estimated area of gold mining throughout the region increased by about 40% between 2012 and 2016 (Asner and Tupayachi 2017). In the Brazilian Amazon, mining significantly increased forest loss up to 70 km beyond mining lease boundaries, causing 11,670 km^2 of deforestation between 2005 and 2015, representing 9% of all Amazon forest loss during this time (Sonter et al. 2015).

Mining is also an important driver of deforestation in African and Asian countries. In the Democratic Republic of Congo, where the second-largest area of tropical forest in the world occurs, mining-related deforestation exacerbated by violent conflict (Butsic et al. 2015). In India, mining has contributed to deforestation at a district level, with coal, iron and limestone having had the most adverse impact on forest area loss (Ranjan, 2019). Gold mining is also identified as a driver of deforestation in Myanmar (Papworth et al. 2017).

7.3.1.4 Fire regime changes

Wildfires (uncontrolled fires that burn in wildland vegetation) account for approximately 70% of the global biomass burned annually (van der Werf et al. 2017) and constitute a large global source of atmospheric trace gases and aerosols (Gunsch et al. 2018). Natural and human-ignited fires affect all major biomes, altering ecosystem structure and functioning (Argañaraz et al. 2015; Engel et al. 2019; Mancini et al. 2018; Nunes et al. 2016; Remy et al. 2017; Aragaão et al. 2018). More than half of the terrestrial surface of the Earth has fire regimes outside the range of natural variability, with changes in fire frequency and intensity posing major challenges for land restoration (Barger et al. 2018). The frequency of fires has increased in many areas, exacerbated by decreases in precipitation, including in many regions with humid and temperate forests that rarely experience large-scale fires naturally. Some changes in fire regimes, particularly in tropical forests, are sufficiently severe that recovery to pre-disturbance conditions may no longer be possible (Barger et al. 2018). In some ecosystems, fire prevention might lead to accumulation of large fuel loads that enable wildfires (Moreira et al. 2020).

About 98 Mha of forest are estimated to have been affected by fire in 2015 (FAO 2020). Fire is a prevalent forest disturbance in the tropics where about 4% of the total forest area in that year was burned and more than two-thirds of the total forest area affected was in Africa and South America (FAO 2020). Fires have many different causes, with land clearing for agriculture the primary driver in tropical regions, for example, clearance for industrial oil-palm and paper-pulp plantations in Indonesia (Chisholm et al. 2016), or for pastures in the Amazon (Barlow et al. 2020). Other socioeconomic factors are also associated with wildfire regimes such as land-use conflict and socio-demographic aspects (Nunes et al. 2016; Mancini et al. 2018). Wildfire regimes are also changing by the influence of climate change, with wildfire seasons becoming longer, wildfire average size increases in many areas and wildfires occurring in areas where they did not occur before (Jolly et al. 2015; Artés et al. 2019). Lightning plays an important role in the ignition of wildfires, with the incidence of lightning igniting wildfires predicted to increase with rises in global average air temperature (Romps et al. 2014).

7.3.1.5 *Logging and fuelwood harvest*

The area of forest designated for production has been relatively stable since 1990. Considering forest uses, about 30% (1.2 billion ha) of all forests is used primarily for production (wood and non-wood forest products), about 10% (424 Mha) is designated for biodiversity conservation, 398 Mha for the protection of soil and water, and 186 Mha is allocated for social services (recreation, tourism, education research and the conservation of cultural and spiritual sites) (FAO 2020). While the rate of increase in the area of forest allocated primarily for biodiversity conservation has slowed in the last ten years, the rate of increase in the area of forest allocated for soil and water protection has grown since 1990, and notably in the last ten years. Global wood harvest (including from forests, other wooded land and trees outside forests) was estimated to be almost 4.0 billion m^3 in 2018 (considering both industrial roundwood and fuelwood) (FAO 2019). Overall, wood removals are increasing globally as demand for, and the consumption of wood products grows annually by 1% in line with growing populations and incomes with this trend expected to continue in coming decades. Over-extraction of wood for timber and fuelwood) is identified as an important driver of mangrove deforestation and degradation (Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Fauzi et al. 2019).

Selective logging is a substantial form of forest degradation in many tropical developing countries, with emissions associated with the extracted wood, incidental damage to the surrounding forest and from logging infrastructure (Pearson et al. 2014). Traditional fuelwood and charcoal continue to represent a dominant share of total wood consumption in low-income countries (Barger et al. 2018). Regionally, the percentage of total wood harvested used as fuelwood varies from 90% in Africa, 62 % in Asia, 50% in South America to less than 25 % in Europe, North America and Oceania. Under current projections, efforts to intensify wood production in plantation forests, together with increases in fuel-use efficiency and electrification, are suggested to only partly alleviate the pressure on native forests (Barger et al. 2018). The adoption of more sustainable production systems continues to be slow, evidenced for example, by a slowdown in the expansion of the area of certified forests.

7.3.2 Anthropogenic direct drivers – Agriculture

7.3.2.1 Livestock numbers and productivity

Enteric fermentation dominates agricultural CH_4 emissions (Section 7.2.3) with emissions being a function of both animal numbers and animal productivity. In addition to enteric fermentation, both CH_4 and N_2O emissions from manure management and deposition on pasture, make livestock the main agricultural emissions source (Tubiello 2019). AR5 reported increases in populations of all major livestock categories between the 1970s and 2000s, including ruminants, the predominant source of enteric fermentation emissions, with increasing numbers directly linked with increasing CH_4 emissions (Smith et al. 2014). The SRCCL identified managed pastures as a disproportionately high emissions source within grazing lands, with *medium confidence* that increased manure production and deposition was a key driver (Jai et al. 2019). Latest data (FAO 2020J3) indicate continued global livestock population growth between 1990 and 2018 (Figure 7.11), including increases of 17% in cattle and buffalo numbers, and 26% in sheep and goat numbers, corresponding with CH_4 emission trends. Data also indicate increased productivity per animal for example, average increases of 13% in beef, 12% in pig meat and 42% in whole (cow) milk per respective animal between 1992 and 2018 (FAO 2020J4). Despite these advances leading to reduced emissions per unit of product (calories, meat and milk) (Tubiello 2019; FAO 2016), increased individual animal productivity generally requires increased inputs (e.g. feed) and this generates increased outputs (e.g. manure), and associated emissions of CH_4 and N_2O (Beauchemin et al. 2020). Increased livestock production is in response to growth in demand for animal-sourced food, driven by a growing human population (FAO 2018), increased consumption resulting from changes in affluence, notably in middle-income countries (Godfray et al. 2018). Available data document increases in total meat and whole milk consumption by 26 and 11% respectively between 1990 and 2013, as indicated by average annual per capita supply (FAO, 2018J1). Sustained demand for animal-sourced food is expected to drive further livestock sector growth, with global production projected to expand by 14% by 2029, facilitated by lower feed prices and stable product prices (OECD-FAO 2019).

Livestock numbers increased in Africa and the Middle East, including ruminants (sheep and goats: + 86%; cattle and buffalo: + 106%), pigs (+ 135%) and poultry (+ 107%) between 1990 and 2018 (Figure 7.11). Similarly, Asia and the Developing Pacific recorded increases in all major livestock categories, particularly poultry (+ 210%) during the same period (FAO 2020J3). Increases in cattle and buffalo (+179%), pig (+179%) and poultry (+179%) numbers were documented in Latin America and the Caribbean, while livestock numbers generally declined in both Developed Countries and Eastern Europe and West-Central Asia, including ruminants (FAO 2020J3), broadly corresponding with regional CH_4 emission trends (Figure 7.9). Data indicate increased animal productivity over the last three decades in all regions, with considerable increases in average sheep meat per animal in Asia and the Developing Pacific (+47%) and average milk yield per animal in both Developed Countries (+56%), and Eastern Europe and West-Central Asia (+64%) between 1992 and 2018 (FAO 2020J4). Data also indicate growth in consumption of animal sourced food in most regions (FAO 2018aJ1). For example, average meat consumption per capita increased by 44% in Asia and the Developing Pacific and by 37% in Africa and the Middle East between 1990 and 2013. Both meat and milk consumption declined (-3% and -24% respectively) in Developed Countries over the same period (FAO 2018J1).

7.3.2.2 Rice cultivation

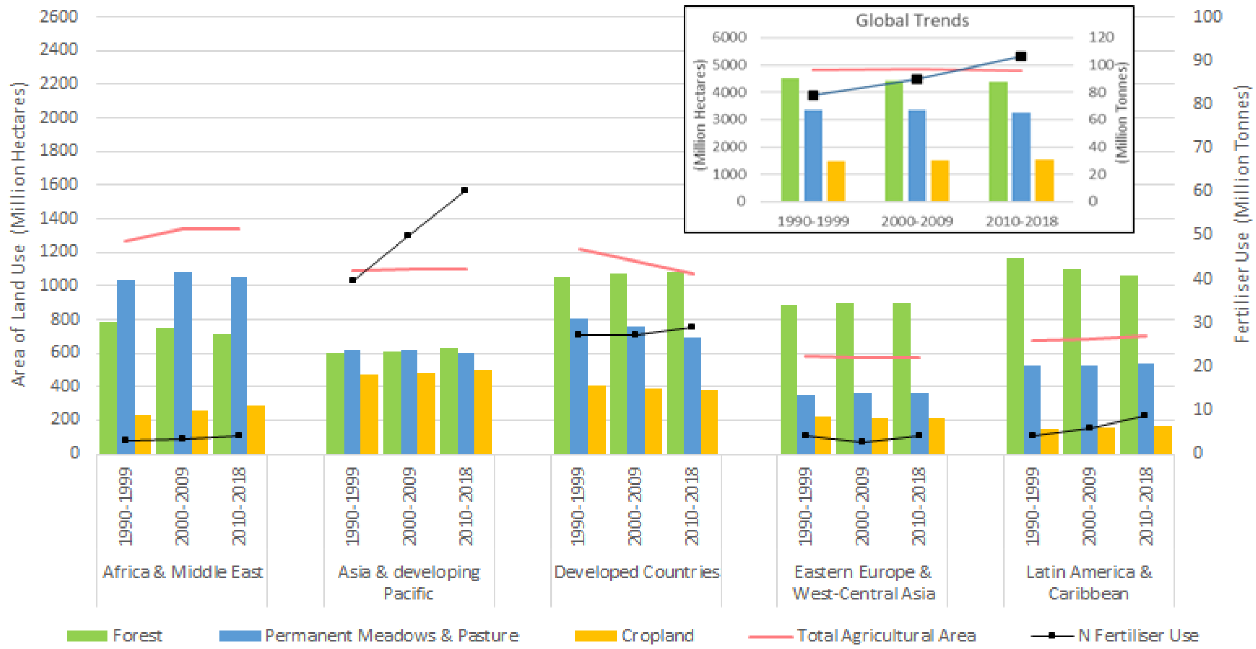
In addition to livestock, both AR5 and the SRCCL identified paddy rice cultivation as an important emissions source (Smith et al. 2014), with *medium evidence* and *high agreement* that its expansion is a key driver of growing trends in atmospheric CH_4 concentration (Jai et al. 2019). Latest data indicate the global harvested area of rice to have grown by 14% between 1990 and 2018, with total paddy production increasing by 51%, from 519 Mt to 782 Mt (FAO 2020J5). Data on consumption suggest a slight increase (+ 6%) in average annual per capita consumption between 1990 and 2013 (FAO 2018bJ2). Global rice production is projected to increase by 13% by 2028 compared to 2019 levels (OECD-FAO 2019). However, yield increases are expected to limit cultivated area expansion, while dietary shifts from rice to protein, as a result of increasing per capita income, is expected to reduce demand in certain regions, with overall, a slight decline in emissions projected to 2030 (USEPA 2019).

In agreement with AR5 and the SRCCL, latest data indicate Asia as accounting for the largest share of rice related emissions (Section 7.2.3) (Smith et al. 2014; Jai et al. 2019). AR5 noted Africa and Europe to have the highest emission growth rates between 2000 and 2010 (Smith et al. 2014). Between 1990 and 2018, Africa and the Middle East recorded the greatest increase (+134%) in area under rice cultivation, followed by Asia and the Developing Pacific (+11%), with area reductions evident in all other regions (FAO 2020J5) broadly corresponding with related regional CH_4 emission (Figures 7.3 and 7.9). Accordingly, overall production increased by 159% in Africa and the Middle East and by 49% in Asia and the Developing Pacific during the same period. However, Latin America and the Caribbean demonstrated an 84% increase in production, although accounted for only 4% of global production over the period on average (FAO 2020J5). Africa and the Middle East had the greatest growth (+ 26%) in consumption (average annual supply per capita) between 1990 and 2013, with little change (+ 1%) observed in Asia and the Developing Pacific (FAO 2018bJ2). Most of the projected increase in global rice consumption is in Africa and Asia (OECD-FAO 2019).

7.3.2.3 Synthetic fertiliser use

Both AR5 and the SRCCL described considerable increases in global use of synthetic nitrogen fertilisers since the 1970s, which was suggested to be a major driver of increasing N_2O emissions (Smith et al. 2014; Jai et al. 2019). Latest data document a 42% increase in global nitrogen fertiliser use between 1990 and 2018 (FAO 2020J2) corresponding with associated increased N_2O emissions (Figure 7.3). Increased fertiliser use has been driven by pursuit of increased crop yields, with for example, a 56% increase in average global cereal yield per hectare observed during the same period (FAO 2020J5), achieved through both increased fertiliser use and varietal improvements (Smith et al. 2014). Increased yields are in response to increased demand for food, feed, fuel and fibre crops which in turn has been driven by a growing human population (FAO 2019), intensification of livestock production (Tian et al. 2020) and bioenergy policy (OECD-FAO 2019). Global crop production is projected to increase by almost 15% over the next decade, with low income and emerging regions with greater availability of land and labour resources expected to experience the strongest growth, and account for about 50% of global output growth (OECD-FAO 2019). Increases in global nitrogen fertiliser use are also projected, notably in low income and emerging regions (USEPA 2019).

A considerable increase in nitrogen fertiliser use occurred in Latin America and the Caribbean (+ 175%) between 1990 and 2018 (FAO, 2020J2), corresponding with, for example, increases in average yield per hectare by 106% for maize, 60% for wheat and 7% for soybean (FAO 2020J5) and a 22% increase in cropland area over the same period (FAO, 2020J1). However, Asia and the Developing Pacific on average accounted for 54% and Developed Countries 31%, of global nitrogen fertiliser use between 1990 and 2018, with both regions, particularly the former, demonstrating increased use (+ 76% and + 8% respectively) over the same period (Figure 7.11). A 36% increase in average paddy rice yield per hectare was observed in Asia and the Developing Pacific, while the area under paddy rice increased by 11% (FAO 2020J5). Eastern Europe and West Central Asia was the only region to demonstrate a reduction in fertiliser between 1990 and 2018 (- 46%).



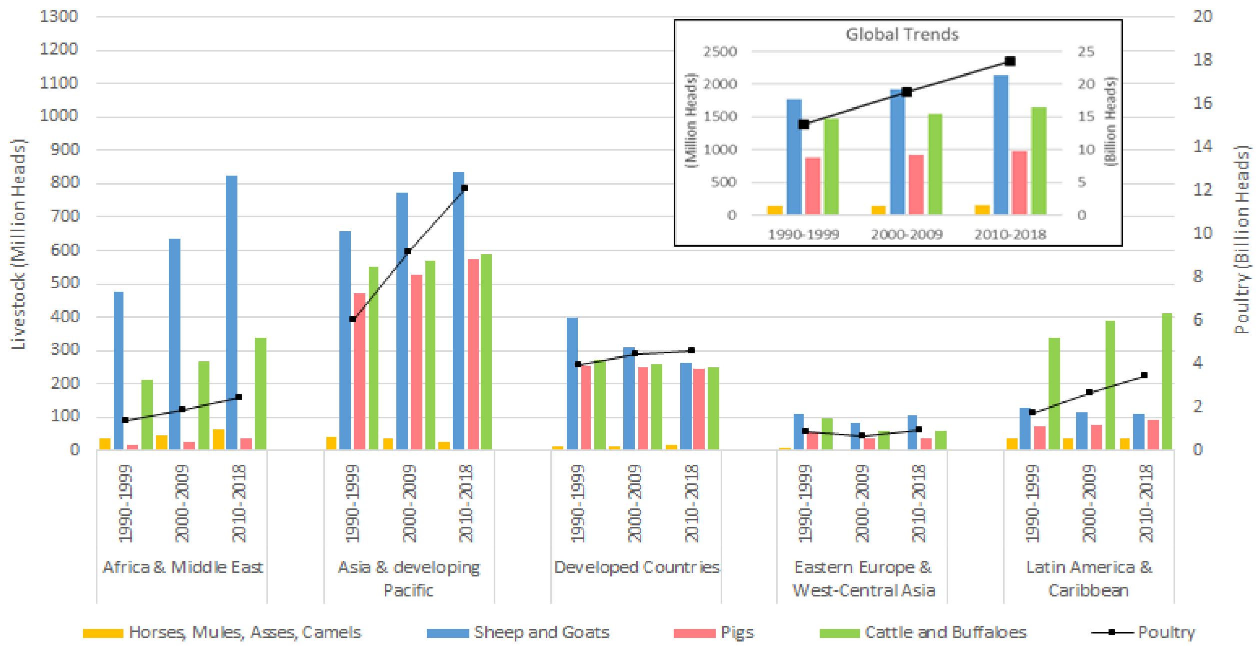


Figure 7.11 Trends in average global and regional land area under specific land uses (FAO, 2020J1), inorganic nitrogen fertiliser use (FAO, 2020J2) (top) and number of livestock (FAO, 2020J3) (bottom) for three decades. For land use classification 'cropland' represents the FAOSTAT category 'arable land' which includes land under temporary crops, meadow, pasture and fallow. 'Forest' and 'permanent meadow and pasture' follow FAOSTAT categories.

7.3.3 Indirect drivers

The indirect drivers behind how humans both use and impact natural resources are outlined in Table 7.3, specifically; demographic, economic and cultural, scientific and technological, and institutional and governance drivers. These indirect drivers not only interact with each other at different temporal and spatial scales but are also subject to impacts and feedbacks from the direct drivers (Barger et al. 2018).

Table 7.3 Indirect drivers of anthropogenic land and natural resource use patterns

Demography	***Global and regional trends in population growth:*** There was a 43% increase in global population between 1990 and 2018. The greatest growth was observed in Africa and the Middle East (+ 104%) and least growth in Eastern Europe and West-Central Asia (+ 7%) (FAO 2019). ***Global and regional projections***: Population is projected to increase by 28% between 2018 and 2050 reaching 9.7 billion (FAO 2019). The world's population is expected to become older, more urbanised and live in smaller households (UN Environment 2019). Africa and the Middle East is expected to continue to have the highest population growth and project to increase by 91% between 2018 and 2050 (FAO 2019). Population growth will be highest in some of the poorest countries with a low carbon footprint per capita and high gender inequity as well as countries going through their early or late demographic dividend (most middle-income and upper middle-income countries) (UN Environment 2019). ***Human migration:*** Growing mobility and population are linked to human migration, a powerful driver of changes in land and resource use patterns at decadal timescales. The stock of migrants in the world now is greater than at any point in the past, with the dominant flow of people being from rural areas to urban settlements over the past few decades, notably in the developing world (Adger et al. 2015; Barger et al. 2018).
Economic development and cultural factors	Changes in land use and management come from individual and social responses to economic opportunities (e.g. demand for a particular commodity or improved market access), mediated by institutions and policies (e.g. agricultural subsidies and low-interest credit or government-led infrastructure projects) (Barger et al. 2018). ***Projections on consumption***: If the future global population adopts a per capita consumption rate similar to that of the developed world, the global capacity to provide land-based resources will be exceeded (Barger et al. 2018). Economic growth in the developing world is projected to double the global consumption of forest and wood products by 2030, with demand likely to exceed production in many developing and emerging economies in Asia and Africa within the next decade (Barger et al. 2018). ***Global trade***: Globalisation increases pressures on land systems and functions, with global trade and capital flow influencing land use, notably in developing countries (UN Environment 2019; Yao et al. 2018; Furumo and Aide 2017; Pendrill et al. 2019). Estimates suggest that between 29 and 39% of emissions from deforestation in the tropics resulted from the international trade of agricultural commodities (Pendrill et al. 2019). ***Culture***: Cultural factors can have a powerful and long-lasting effect on how individuals, communities, and nations relate to environmental opportunities and challenges. Among them, diet is a critical factor in interaction with economic development impacts the use of natural resources (Barger et al. 2018) (Section 7.4.5).
Science and technology	Technological factors operates in conjunction with economic drivers of land use and management, whether through intensified farming techniques and biotechnology, high-input approaches to rehabilitating degraded land (e.g. Lin et al. 2017; Guo et al. 2020) or through new forms of data collection and monitoring (e.g. Song et al. 2018; Thyagharajan et al. 2019; Arévalo et al. 2020).

	Changes in farming systems*:** Fast advancing technologies shape production and consumption and drive land-use patterns and terrestrial ecosystems at various scales. Innovation is expected to drive increases in global crop production during the next decade (OECD-FAO 2020). Technological changes were significant for the expansion of soybean in Brazil by adapting to different soils and photoperiods (Abrahão and Costa 2018). In Asia, technological development changed agriculture with significant improvements in yields (Briones and Felipe 2013). Research and technological advancement in, for example, crop science, agronomy and precision agriculture is recognised as critical in facilitating sustainable intensification - allowing increased production in tandem with environmental conservation, including GHG mitigation (Thomson et al. 2019; Cassman and Grassini 2020. Developments such as precision agriculture and drip irrigation have facilitated more efficient agrochemical and water use (UN Environment 2019). ***Emerging mitigation technologies: New approaches with considerable CH_4 mitigation potential are expected to be commercially available in the next five years, such as chemically synthesised methanogen inhibitors for ruminants (McGinn et al. 2019; Melgar et al. 2020; Beauchemin et al. 2020) (see Section 7.4.3). There is growing literature (in both academic and non-academic sphere) on the biological engineering of protein. Although in its infancy and subject to investment, technological development, regulatory approval, and consumer acceptance, it is suggested to have the potential to disrupt current livestock production systems and land use (Stephens et al. 2018; Ben-Arye and Levenberg 2019; ThinkX 2019; Post et al. 2020). The extent to which this is possible and the overall climate benefits are unclear (Lynch and Pierrehumbert 2019; Chriki and Hocqueete, 2020).
Institutions and governance	Institutional factors often moderate the relevance and impact of changes in economic and demographic variables related to resource exploitation and use. Institutions encompass the rule of law, legal frameworks and other social structures (e.g. civil society networks and movements) determining land management (e.g. formal and informal property rights, regimes and their enforcement); information and knowledge exchange systems; local and traditional knowledge and practice systems) (Barger et al. 2018) ***Land rights***: Land tenure often allows communities to exercise traditional governance based on traditional ecological knowledge, devolved and dynamic access rights, judicious use, equitable distribution of benefits (Mantyka-Pringle et al. 2017; Thomas et al. 2017; Wynberg 2017), biodiversity (Contreras-Negrete et al. 2015; Novello et al. 2018) and fire and grazing management (Levang et al. 2015, Varghese et al. 2015). Land tenure security affects land use and outcomes (Chigbu et al. 2017; Robinson et al. 2018) notably concerning land grabbing (i.e. large-scale acquisition of land) which is currently a prominent driver of land system change, especially in developing countries (Barger et al. 2018; Anseeuw et al. 2011; Marselis et al. 2017; McMichael 2013). ***Agreements and Finance:*** Since AR5, global agreements were reached on climate change, sustainable development goals, and the mobilisation of finance for development and climate action. Several countries adopted policies and commitments to restore degraded land (Barger et al. 2018). Companies have also made pledges to reduce impacts on forests and on the rights of local communities as well as eliminating deforestation from their supply chains. The finance sector has also started to make explicit commitments to avoiding environmental damage (Barger et al. 2018).

7.4 Assessment of AFOLU mitigation measures including trade-offs and synergies

AFOLU or land-based climate change mitigation, can be delivered through a variety of land management or consumer practices that reduce GHG emissions and/or enhance carbon sequestration within the land system (i.e. in forests, wetlands, croplands or grasslands). Measures that result in a net removal of GHGs from the atmosphere and storage in either living or dead organic material, or in geological stores, are referred to as CO_2 removal (CDR), greenhouse gas removal (GGR) or negative emissions technologies (NETs) in previous IPCC reports (Rogelj et al. 2018; Jia et al. 2019). This section evaluates current knowledge and latest scientific literature on AFOLU mitigation measures and potentials, including land-based CDR measures. Section 7.4.1 provides an overview of the approaches for estimating mitigation potential, the co-benefits and risks from land-based mitigation measures, estimated global and regional mitigation potential and associated costs according to literature published over the last decade. Subsequent subsections assess literature on 20 key AFOLU mitigation measures specifically providing:

- A description of activities, co-benefits, risks and implementation opportunities and barriers
- A summary of conclusions in AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL)
- An overview of literature and developments since the AR5 and IPCC Special Reports
- An assessment and conclusion based on current evidence

Measures are categorised as supply-side activities in (1) forests and other ecosystems, (2) agriculture, and (3) bioenergy and other land-based energy technologies, and (4) demand-side activities (Table 7.5). In addition, several information boxes are dispersed within the section and provide supporting material, including relevant definitions (Box 7.2) and case studies exploring a range of topics from climate-smart forestry in Europe (Box 7.3), agroforestry in Brazil (Box 7.4), sustainable rice management (Box 7.5), climate-smart village approaches (Box 7.6), farm systems approaches (Box 7.7) and mitigation within Indian agriculture (Box 7.8). Information specifically on bioenergy and BECCS, including relevant terminology (Box 7.9) and how mitigation estimates are calculated (Box 7.10) is provided in Section 7.4.4. Novel land-based mitigation measures, including enhanced weathering and novel foods are covered in Chapter 12. In addition, as mitigation within AFOLU concerns land management and use of land resources, AFOLU measures impact other sectors. Accordingly, AFOLU measures are also discussed in other sectoral chapters, notably demand-side solutions (Chapter 5), bioenergy and Bioenergy with Carbon Capture and Storage (BECCS) (Chapter 6), the use of wood products and biomass in buildings (Chapter 9), and CDR measures, food systems and land related impacts, risks and opportunities of mitigation measures (Chapter 12).

7.4.1 Introduction and overview of mitigation potential

7.4.1.1 Estimating mitigation potentials

Mitigation potentials for AFOLU measures are estimated by calculating the scale of emissions reductions or carbon sequestration against a counterfactual scenario without mitigation activities. The types of mitigation potential estimates in recent literature include: (1) technical potential (the biophysical potential or amount possible with current technologies), (2) economic potential (constrained by costs, usually by a given carbon price (Table 7.4), (3) sustainable potential (constrained by environmental safeguards and/or natural resources, e.g. limiting natural forest conversion), and (4) feasible potential (constrained by environmental, socio-cultural, and/or institutional barriers), however, there are no set definitions used in literature.

Approaches to estimating mitigation potentials include individual action and sectoral assessments (henceforth referred to as sectoral assessments), and integrated assessments across sectors. Sectoral assessments include studies focusing on one activity based on spatial and biophysical data, as well as econometric and optimisation models for a sector, e.g. the forest or agriculture sector, and therefore cover a large suite of practices and activities while representing a broad body of literature. Sectoral assessments however, rarely capture cross-sector interactions or impacts, making it difficult to completely account for land competition, trade-offs, and double counting when aggregating sectoral estimates across different studies and methods (Smith et al. 2014, Jia et al. 2019). On the other hand, integrated assessment models (IAMs) assess the climate impact of multiple and interlinked practices across sectors and therefore, can account for interactions and trade-offs (including land competition, use of other resources and international trade) between them. However, the number of land-based measures used in IAMs are more limited compared with the sectoral portfolio (Section 7.5). The resolution of land-based measures in IAMs are also generally coarser compared to some sectoral estimates, and as such, may be less robust for individual measures. Given the differences between and strengths and weaknesses of the two approaches, it is helpful to compare the estimates from both.

This section reviews mitigation potential estimates largely from sectoral approaches, and where data is available, compares them to IAM estimates. Integrated assessment models and the emissions trajectories, cost-effectiveness and trade-offs of various mitigation pathways are detailed in Section 7.5. It should be noted that the underlying literature for sectoral as well as IAM mitigation estimates consider a range of GWP_{100} IPCC values to convert CH_4 and N_2O to CO_2-eq. Where possible, we note the various GWP_{100} values (in IAM estimates, and the wetlands and agriculture sections), however the varying GWP_{100} values used across studies prevents description of non-CO_2 gases in native units as well as conversion to AR6 GWP_{100} CO_2-eq values to aggregate sectoral assessment estimates.

7.4.1.2 Co-benefits and risks

Land interventions have interlinked implications for climate mitigation, adaptation, food security, biodiversity, ecosystem services, and other environmental and societal challenges (Section 7.6.5). Therefore, it is important to consider the net effect of mitigation measures for achieving both climate and non-climate goals (Section 7.1). The SRCCL conducted a detailed assessment on the impacts and trade-offs of land-based measures (Smith et al. 2019a), and concluded that many land management options have the potential to mitigate climate change while also addressing other land challenges; adaptation, desertification, land degradation and enhance food security; as well as contributing to SDGs and Nature's Contributions to People (NCP) (*high confidence*). Five of the 26 land management options that were examined in the SRCCL (increased food productivity; reduced deforestation and forest degradation; increased soil organic carbon content; fire management; and reduced post-harvest losses) had large mitigation potential (>3 $GtCO_2$-eq yr^{-1}) without adverse impacts on the other four land challenges (*high confidence*). Approximately 50% of the 40 land management, value-chain management and risk management response options (primarily agriculture- and soil-based land management options, and ecosystem-based land management options) were found to deliver co-benefits or no adverse side effects for the full range of SDGs and NCPs (*medium confidence*).

Potential co-benefits, risks, and strategies for maximising benefits and reducing risks are outlined for each of the 20 land-based mitigation measures in the proceeding sub-sections and summarised in Tables 7.6-7.8. Section 7.6.5. discusses general links with ecosystem services, human well-being and adaptation, while Chapter 12 (Section 12.5) provides further, in-depth assessment of the land related impacts, risks and opportunities associated with mitigation options across sectors, including positive and negative effects on land resources, water, biodiversity, climate, and food security. While it is helpful to assess the general benefits, risks and opportunities possible for land-based mitigation measures (Smith et al. 2019a), their efficacy and scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g. scale, method), and context (e.g. biome, climate, food system, land ownership) that vary geographically and over time (Smith et al. 2019a; 2019b; Hurlbert et al. 2019; Chapter 12, Section 12.5) *(robust evidence, high agreement).* Impacts of land-based mitigation measures are therefore highly context specific and conclusions from specific studies may not be universally applicable. The negative consequences of inappropriate or misguided design and implementation of measures may be considerable, potentially impacting for example, mitigation longevity, biodiversity, wider ecosystem functioning, livelihoods, food security and human well-being. (Cross Chapter Box on Nature-based Solutions using Natural Ecosystems: Synergies and trade-offs for adaptation of natural and human systems to ACC, AR6 WGII). Conversely, if implemented at appropriate scales and in a sustainable manner, land-based mitigation practices have the capacity to reduce emissions and sequester billions of tonnes of carbon from the atmosphere over coming decades, while also helping to address soil degradation and biodiversity loss, enhance water quality and supply, improve food security, and positively contribute to ecosystem health livelihoods and human wellbeing *(high confidence)* (Toensmeier 2016; Francis 2016; Smith et al. 2019). Accordingly, it is widely recognised that systematic land-use planning that is context-specific and adaptable over time can help achieve land-based mitigation that maximises and capitalises on co-benefits and avoids or limits trade-offs with other environmental and socio-economic goals (Longva et al. 2017; Section 7.6; Chapter 12).

7.4.1.3 Overview and assessment of global and regional potentials

Since the AR5, there have been numerous new global assessments of sectoral land-based mitigation potential (Fuss et al. 2018; Griscom et al. 2017; Griscom et al. 2020; Roe et al. 2019; Smith et al. 2016; Jia et al. 2019) as well as IAM estimates of mitigation potential (Frank et al. 2019; 2020; Baker et al. 2019; Doelman et al. 2019; Johnston and Radeloff 2019; Popp et al. 2017; Riahi et al. 2017; Rogelj et al. 2018).

The SRCCL identified reduced deforestation and forest degradation to have greatest potential for reducing supply-side AFOLU emissions (0.4–5.8 $GtCO_2$-eq yr^{-1}) (*high confidence*) followed by combined agriculture measures, 0.3–3.4 $GtCO_2$-eq yr^{-1} (*medium confidence*), while shifting towards healthy, sustainable diets (0.7–8.0 $GtCO_2$-eq yr^{-1}) (*high confidence*) followed by reduced food loss and waste (0.8–4.5 $GtCO_2$-eq yr^{-1}) (*high confidence*) had the highest demand-side potential (Jia et al. 2019). Measures with greatest potential for CDR were afforestation/reforestation (0.5–10.1 $GtCO_2$-eq yr^{-1}) (*medium confidence*), soil carbon sequestration in croplands and grasslands (0.4–8.6 $GtCO_2$-eq yr^{-1}) (*high confidence*) and BECCS (0.4–11.3 $GtCO_2$-eq yr^{-1}) (*medium confidence*). All estimates concerned the period 2030-2050, and included the full range of technical, economic and sustainability mitigation potentials. The SRCCL did not explore regional potential, associated feasibility nor provide detailed analysis of costs.

Since the SRCCL, updated mitigation estimates for the period 2020-2050 are provided in Table 7.4 for global potential at varying carbon prices according to sectoral assessments and IAMs, and in Table 7.5 and Figure 7.12 for global and regional potential, disaggregated by technical and economic potentials. The mean potential between 2020-2050 provides a good approximation of the amount of mitigation that could be available in 2030. There is not a sizeable difference in the global technical potential ranges (Tables 7.4 and 7.5) since the SRCCL, with the exception of the global technical potentials for agroforestry and food waste and the economic potentials for reduced deforestation, which have since increased (Table 7.5). An important development however, is the new regional disaggregation of technical and economic (USD 100/tCO_2-eq yr^{-1}) mitigation potentials for 20 AFOLU measures, including cost-effective potential for demand-side and soil organic carbon sequestration in croplands and grasslands, not estimated before (Roe et al. under review).

When the regional economic (up to USD 100/tCO_2-eq yr^{-1}) potentials are aggregated across forestry and other ecosystems, agricultural and demand side measures (excluding BECCS and land-use change effects in demand-side measures; more detail to minimise double counting outlined in Table 7.5), the total global mitigation potential is estimated to be 11.9 ±3.1 $GtCO_2$-eq yr^{-1} for the period 2020-2050, with about 50% from forests and other ecosystems, 30% from agriculture and 20% from demand-side measures (Roe et al. under review). Supply-side measures account for approximately 8.7 ±3.1 $GtCO_2$-eq yr^{-1} in the aggregated regional estimates, in line with the 9.1 $GtCO_2$-eq yr^{-1} median (6.7 – 12.3 range) estimate across global studies (LULUCF + Agriculture in Table 7.4). These supply-side estimates are also in line with the AR5 estimate of 7.2-10.6 $GtCO_2$-eq yr^{-1} in 2030 at USD 100/tCO_2-eq yr^{-1} (Smith et al. 2014).

In the IAMs, the economic AFOLU (agriculture and land-use change measures) potential up to USD 100/tCO_2-eq yr^{-1} is 4.1 median (-0.1 - 9.5 range) $GtCO_2$-eq yr^{-1} averaged between 2020 and 2050, and 6.8 (-0.2 - 10.5) $GtCO_2$-eq yr^{-1} in 2050 (Table 7.4). The IAM potential is substantially lower, about half of the sectoral potential when averaged between 2020-2050. The differences between the two types of estimates are largely due to: (1) IAMS including a smaller portfolio of AFOLU measures compared to the sectoral estimates; (2) the baseline scenarios in some IAMs already including low carbon prices and seeing considerable mitigation, particularly from land-use change, which limits the mitigation potential in the USD 100/tCO_2-eq yr^{-1} scenario; and (3) most IAM estimates including temperature over-shoot scenarios, placing most mitigation, particularly of CDR measures, after 2050 (Section 7.5).

Using a sectoral approach, reduced conversion (protection), enhanced management, and restoration of forests, wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester carbon by 6.1 (±2.9) $GtCO_2$-eq yr^{-1}, with measures that 'protect' having the highest mitigation densities (mitigation per area) (Figure 7.12). Agriculture provides the second largest share of mitigation, with 3.9 ± 0.2 $GtCO_2$-eq yr^{-1} potential (up to USD 100/tCO_2-eq), from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to healthy diets and reducing food waste, can provide 1.9 $GtCO_2$-eq yr^{-1} potential (accounting only for diverted agricultural production and excluding land-use change). Demand-side measures reduces agricultural land needs and land competition, therefore potentially complementing and enabling supply-side measures such as reduced deforestation and reforestation.

Regionally, economic mitigation potential up to USD 100/tCO_2-eq yr^{-1} is estimated to be greatest in tropical countries in Asia and developing Pacific (33%), Latin America and the Caribbean (25%), and Africa and the Middle East (20%) because of the large potential from reducing deforestation and sequestering carbon in forests and agriculture (Figure 7.12). However, there is also considerable potential in Developed Countries (17%) and Eastern Europe and West-Central Asia (6%). These results are in line with the IAM regional mitigation potentials (Table 7.5, Section 7.6). The proportions of economic potentials compared to technical potentials are relatively lower in the later two regions because of the higher costs of implementation. The protection of forests and other ecosystems is the dominant source of mitigation potential in tropical regions, sequestering carbon through agriculture measures is important in Developed Countries and Eastern Europe and West-Central Asia, and demand-side measures are key in Developed Countries and Asia and developing Pacific. As expected, the highest total potential is associated with countries and regions with large land areas, however when considering mitigation density (total potential per hectare), many smaller countries, including small island states have disproportionately high levels of mitigation for their size (Figure 7.12).

Although economic potentials provide more realistic, near-term climate mitigation compared to technical potentials, they still do not account for feasibility barriers and enabling conditions that vary by region and country. For example, according to most models, including IAMs, avoided deforestation is the cheapest land-based mitigation option (Table 7.4), however implementing interventions aimed at reducing deforestation (including REDD+) often have higher transaction and implementation costs than expected due to various barriers and enabling conditions (Luttrell et al. 2018; Section 7.6). The feasibility of implementing AFOLU mitigation measures, including those with multiple co-benefits, depends on varying economic, technological, institutional, socio-cultural, environmental and geophysical barriers (*high confidence*) (Smith et al. 2019a). While Tables 7.6-7.8 provide an overview of co-benefits and risks associated with individual mitigation measure, Section 7.6.6 provides a feasibility assessment for a sub-set of mitigation measures, outlining key enabling factors and barriers following methodology used by other sectoral chapters.

Table 7.4 Estimated annual mitigation potential ($GtCO_2$-eq) by category and carbon price across sectoral studies (Sec) and integrated assessment models (IAM), based on updated data from (Roe et al. 2019) and the IPCC AR6 database (Section 7.5). Sectoral estimates use a range of GWP values and IAMs use GWP_{100} IPCC AR5 values; CH_4 = 28, N_2O = 265. Estimates represent the median, and full range of potential, averaged for the years 2020-2050 and also provided for 2050 (noted under the mitigation estimate column). Numbers are summed over the price ranges. The sectoral aggregated potentials are the sum of global estimates for the measures in Table 7.5 related to Agriculture, BECCS and Demand-side (see Table 7.5 caption for specific measures included). To facilitate the comparison between sectoral and IAM estimates, sectoral estimates are also provided for the same measures as those included in IAMs (in italics). The sectoral and IAM estimates reflected here do not account for the substitution effects of avoiding fossil fuel emissions nor emissions from other more energy intensive resources/materials. Mitigation potential from substitution effects are included in the other sectoral chapters like energy, transport, buildings and industry. Agriculture and LULUCF = AFOLU mitigation. Because of some overlaps between measures, sectoral values from BECCS and demand-side measures should not be summed with AFOLU. ND = not determined. Sec = as assessed by sectoral models, IAM = as assessed by integrated assessment models. EJ = ExaJoule primary energy

	Mitigation estimate	< USD 20 / tCO_2-eq	< USD 50 / tCO_2-eq	< USD 100 / tCO_2-eq	Technical ($GtCO_2$-eq yr^{-1})
Agriculture	Sec 2020-2050 avg	1.4 (1.2-2.3)	2 (2-2)	2.3 (1.7-3.6)	7.7 (2.2-28.5)
	Sec Non-CO_2 only	*0.3 (0.2-1.1)*	*0.3 (0.3-0.3)*	*0.4 (0.2-1.2)*	*1.7 (1.1-3.2)*
	IAM 2020-2050 avg	0.6 (-0.3 - 2.7)	0.9 (-0.1 - 3.1)	1.6 (0.3 - 3.3)	
	IAM 2050	0.8 (-0.5 - 2.3)	1.5 (0 - 4.5)	2.3 (-0.1 - 4.9)	
LULUCF	Sec 2020-2050 avg	3 (2.2-4)	4.2 (3.1-5.4)	6.8 (5-8.7)	8.2 (3.1-22.6)
	Sec AR and defor. only	*1.8 (1.4-2.7)*	*3.8 (2.8-5.1)*	*4.9 (4-5.9)*	*5.1 (1.2-15.9)*
	IAM 2020-2050 avg	1 (-0.5 - 3.3)	2 (-0.1 - 4.3)	2.4 (-0.7 - 8.6)	
	IAM 2050	1.2 (-0.4 - 3.3)	3.5 (-0.1 - 4.7)	4.1 (-1.4 - 5.6)	
BECCS [1]	Sec 2020-2050 avg	0	0	0.8 (0.8-3.5)	5.0 (0.5-11.3)
	IAM 2020-2050 avg	0 (0 - 0.3)	0.1 (0 - 1.1)	0.6 (0 - 2.8)	
	IAM 2050	0 (0 - 0.5)	0.2 (0 - 2.7)	0.8 (0 - 6.3)	
Demand-side measures	Sec 2020-2050 avg	ND	ND	ND	7.3 (0.9-18.3)
	IAM 2050	ND	ND	ND	ND
Bioenergy from residues	Sec 2020- 2050 avg	ND	ND	ND	Up to 57 EJ yr^{-1}

[1] Values only consider the carbon dioxide removal (CDR) via geological storage component from BECCS and not potential mitigation derived from the displacement of fossil fuel use in other sectors.

Table 7.5 Global and regional annual mitigation potential for 2020-2050, by measure ($MtCO_2$-eq) from sectoral studies (Sectoral) and integrated assessment models (IAM). The global sectoral estimates are based on a large literature review adapted and updated from (Roe et al. 2019). The regional sectoral estimates are based on studies with regional disaggregation (noted in the Ref column) and reported in Roe et al. Under Review. The IAM estimates were derived from the IPCC AR6 database, reported in Section 7.5. IAMs use GWP_{100} IPCC AR5 values and the sectoral literature use either AR4 or AR5 values. The global estimates represent the full range (in parentheses) from studies published after 2009, separated into technical potential (possible biophysically, with current technologies), and economic (possible given economic constraints, across a range of carbon prices). Median estimates are calculated for categories with 3 or more data points. The regional estimates are taken from spatially explicit data sources, providing a range if there is more than one data source available. The regional economic potential estimates represent available potential for a carbon price of USD 100/tCO_2. Not all options for land management potentials are additive, as some may compete for land. Sectoral estimates reflect a range of methodologies that may not be directly comparable or additive. When reporting aggregate potentials (in Section 7.4.1.3) of regional estimates, we exclude land-use measures that may overlap to minimise any double counting (BECCS, HWPs, reduced peatland conversion, and land-use related avoided emissions in diet shifts and reduced food waste).

Large global potential: > 3000 $MtCO_2$-eq yr^{-1}	**Large regional potential: > 1000 $MtCO_2$-eq yr^{-1}**
Moderate global potential: 300 – 3000 $MtCO_2$-eq yr^{-1}	**Moderate regional potential: 100-1000 $MtCO_2$-eq yr^{-1}**
Small global potential: < 300 $MtCO_2$-eq yr^{-1}	**Small regional potential: < 100 $MtCO_2$-eq yr^{-1}**

Mitigation measure	Definition	Est	Global		Refs (Global)	Africa and Middle East		Asia and developing Pacific		Developed Countries		Eastern Europe and West-Central Asia		Latin America and Caribbean		Refs (Regional)
Forests and other ecosystems			Sectoral	IAM		Sectoral	IAM	Sectoral	IAM	Sectoral	IAM	Sectoral	IAM	Sectoral	IAM	
Reduce deforestation	Reducing deforestation and forest degradation is the conservation of existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance.	Tech	1485 (704 - 5800)		Baccini et al 2017; Bossio et al 2020; Busch & Engelmann 2017; Busch et al 2019; Carter 2015; Favero et al 2020; Federici et al 2015; Griscom 2017; Griscom 2020; Houghton & Nassikas 2018; Houghton et al 2015; Project Drawdown 2020; Smith et al 2013; Zarin 2016	948 - 2213		573 - 2415		0 - 0		0 - 0		1766 - 3935		Busch et al 2019, Austin et al 2020
		Econ	2649 (1206 - 7000)			710 - 1215		295 - 1574		0 - 0		0 - 0		787 - 2493		

Afforestation and/or Reforestation	Afforestation and reforestation (A/R) are activities that convert land to forest, where reforestation is on land that has previously contained forests and afforestation is on land that historically has not contained forest	Tech	2710 (543 - 10124)		Bastin et al 2019; Busch et al. 2019; Doelman et al 2020; Dooley and Kartha 2018; Favero et al 2020; Fuss 2018; Griscom et al 2017; Griscom et al 2020; Houghton & Nassikas 2018; Houghton et al 2015; Kreidenweis 2016; Lenton 2010; Lenton 2014; Lewis et al 2019; Liu et al 2016; McLaren 2012; Sonntag et al 2016; Project Drawdown 2020	192 - 3035		1535 - 1781		0 - 2296		0 - 163		1978 - 3518		Busch et al 2019, Austin et al 2020
		Econ	1670 (190 - 4900)			101 - 399		209 - 266		0 - 291		0 - 30		345 - 898		
Improved and sustainable forest management	Sustainable forest management is the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfil, now and in the future, relevant ecological, economic, and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems	Tech	1810 (1026 - 2100)		Favero et al 2020; Golub et al 2009; Griscom 2017; Sasaki et al 2012; Sasaki et al 2016	205 - 248		421 - 650		366 - 791		202 - 251		86 - 439		Griscom et al 2017; Austin et al 2020
		Econ	894 (320 - 2840)			179 - 186		193 - 313		215 - 220		82 - 151		62 - 204		
Fire management (forest, savanna and grasslands)	Fire management is aimed at safeguarding life, property, and resources through the prevention, detection, control, restriction, and suppression of fire in forests and other ecosystems, including grasslands and savannas.	Tech	(480 - 1760)		Arora et al., 2018; Griscom 2017; Tacconi 2016	84		0		7		0		13		Griscom et al 2017
		Econ				25		0		2		0		4		
Reduce conversion of savannas and grasslands	Reducing the conversion of grasslands and savannas to croplands prevents soil carbon losses by oxidation, and to a smaller extent, biomass carbon loss due to vegetation clearing	Tech	160 (116 - 400)		Bossio et al 2020; Griscom 2017; Kruase et al 2017; Poeplau et al 2011; Project Drawdown 2020											
		Econ	35 (35 - 35)													
Reduce conversion and degradation of peatlands	Reducing the conversion of peatlands avoids emissions of above- and below-ground biomass and soil carbon due to vegetation clearing, fires and peat decomposition from drainage.	Tech	692 (514 - 2021)		Hooijer et al 2010; Bossio et al 2020; Griscom 2017; Griscom et al 2020; Humpenöder et al 202;. Project Drawdown 2020	56		661		23		7		6		Griscom et al 2020
		Econ	452 (54 - 678)			50		595		20		6		6		
Peatland restoration	Peatland restoration involves restoring degraded and damaged peatlands, for example through rewetting and	Tech	713 (488 - 1000)			45		483		147		114		23		Griscom et al 2020

	revegetation, which both increases carbon sinks and also avoids ongoing CO_2 emissions.	Econ	0 (149 - 738)		Bossio et al 2020; Couwenberg 2010; Griscom 2017; Griscom et al 2020; Humpenöder et al 2020; Joosten & Couwenberg 2009; Project Drawdown 2020	22		232		71		55		11		
Reduce conversion of coastal wetlands	Reducing conversion of coastal wetlands, including mangroves, marshes and seagrass ecosystems, avoids emissions from above and below ground biomass and soil carbon through avoided degradation and/or loss.	Tech	230 (67 - 2250)		Donato et al 2011; Griscom et al 2017; Griscom et al 2020; Howard et al 2017; Kauffman et al 2017; Pendleton et al 2012; Project Drawdown 2020	2		108		5		0		14		Griscom et al 2020
		Econ	182 (60 - 273)			1		32		1		0		4		
Coastal wetland restoration	Coastal wetland restoration involves restoring degraded or damaged coastal wetlands including mangroves, salt marshes, and seagrass ecosystems	Tech	173 (36 - 841)		Bossio et al 2020; Griscom 2017; Griscom 2020; Project Drawdown 2020	2		8		0		0		7		Griscom et al 2020
		Econ	(52 - 200)			1		2		0		0		2		
Agriculture																
Soil carbon management in croplands	Practices that increase soil organic matter in croplands include (1) crop management (e.g. improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology), (2) nutrient management, (3) reduced tillage intensity and residue retention, (4) improved water management (e.g. drainage of waterlogged mineral soils and irrigation of crops in arid / semi-arid conditions), (5) improved rice production and (6) biochar application	Tech	1468 (400 - 6780)		Griscom 2017; Lal et al 2004; McLaren 2012; Paustian 2016; Popelau and Don 2015; Powlson 2014; Project Drawdown 2020; Zomer 2017	179		377		234		120		114		Soils Revealed 2020
		Econ	300 (248 - 372)			161		340		211		108		103		
Soil carbon management in grasslands	Practices that increase soil organic matter in grasslands include (1) management of vegetation (e.g. improved grass varieties/sward composition, deep rooting grasses, increased productivity, (2) nutrient management, (3) animal management (e.g. appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification), and 4) fire management	Tech	823 (150 - 2560)		Conant 2017; Dickie et al 2014; Griscom 2017; Henderson et al 2015; Herrero 2016; Lal et al 2010; Paustian et al 2016; Project Drawdown 2020	408		276		423		101		280		Soils Revealed 2020
		Econ	298 (132 - 750)			245		165		254		61		168		
Agroforestry	Agroforestry is a set of diverse land management systems that integrate woody biomass (including trees and woody	Tech	1807 (280 - 9400)			921		1842		1323		883		637		Chapman et al 2020

	shrubs) with crops and/or livestock in space and/or time, sequestering carbon in vegetation and soil	Econ	(439 - 931)		Bossio et al 2020; Chapman et al. 2020; Dickie et al 2014; Griscom et al 2017; Griscom et al 2020; Project Drawdown 2020; Zomer et al 2016	184		368		265		177		127		
Biochar application	Converting biomass into biochar through pyrolysis stabilises carbon, delivering long term carbon storage when applied to soil	Tech	1918 (246 - 6600)		Bossio et al 2020; Dickie et al 2014; Fuss 2018; Griscom 2017; Lee & Day 2013; Lenton 2010; Lenton 2014; Powell and Lenton 2012; Pratt and Moran 2010; Project Drawdown 2020 Roberts et al 2010; Smith 2016; Woolf et al 2010	84		394		387		57		181		Griscom et al 2017
		Econ	600 (331 - 1250)			25		118		116		17		54		
Enteric fermentation	Reducing CH4 emissions from enteric fermentation can be direct (i.e. targeting ruminal methanogenesis and emissions per animal or unit of feed consumed) or indirect, by increasing production efficiency (i.e. reducing emission intensity per unit of product), and can be classified as measures relating to (1) feeding, (2) supplements, additives and vaccines, and (3) livestock breeding and wider husbandry	Tech	910 (680 - 1180)		Beach et al 2015; Caro et al 2016; Dickie et al 2014; EPA 2019; Frank et al 2018; Griscom 2017; Henderson et al. 2015; Herrero et al 2016; Hristov et al 2013	22		58		68		2		31		Beach et al 2015
		Econ	174 (120 - 264)	468 (81 - 1226		19	58.8 (0.3 - 201.6)	33	228.7 (21.2 - 586)	26	49.4 (12.9 - 179.4)	2	11.7 (2.4 - 43.8)	19	118.9 (43.9 - 239)	
Improve manure management	Improving manure storage and deposition reduces CH4 and N2O emissions, and measures may include (1) anaerobic digestion, (2) applying nitrification or urease inhibitors to stored manure or urine patches, (3) composting, (4) improved storage and application practices, (5) grazing practices and (6) alteration of livestock diets to reduce nitrogen excretion	Tech	0 (260 - 470)		Beach et al 2015; Dickie et al 2014; EPA 2019; Herrero et al 2016; Kalt et al 2020	1		33		81		1		2		Beach et al 2015
		Econ	0 (10 - 100)	104 (37 - 314		0	3.6 (0 - 36.3)	27	40.8 (9.8 - 81.2)	63	47.5 (26.8 - 73.5)	0	5.3 (0.1 - 19.9)	1	7 (0.5 - 103.3)	
Improve rice cultivation	Improving rice production reduces CH4 and N2O emissions through measures that (1) improve water management (e.g. single drainage and multiple drainage practices), (2) improve residue management and (3) improve fertiliser application or soil amendments	Tech	243 (120 - 813)		Beach et al 2015; Dickie et al 2014; EPA 2019; Golub et al 2009; Griscom 2017; Hussain et al 2015; Paustian et al 2016; Project Drawdown 2020	8 - 17		189 - 231		6 - 9		0 - 1		10 - 15		Beach et al 2015; Griscom et al 2020
		Econ	119 (53 - 300)	129 (30 - 273		7 - 10	6.8 (-0.1 - 20)	139 - 156	107 (23.8 - 220.8)	4 - 7	9.3 (3.5 - 15.6)	0 - 0	0.6 (0 - 4.1)	6 - 13	5.3 (2.2 - 12.4)	
Crop nutrient management	Improving nutrient management to reduce N2O emissions include optimising fertiliser application rate, fertiliser type (organic manures, compost, and mineral), timing, precision application, and nitrification inhibitors	Tech	100 (60 - 706)		Beach et al 2015; Dickie et al 2014; EPA 2019; Golub et al 2009; Griscom 2017; Griscom et al 2020; Paustian 2016; Project Drawdown 2020; Smith et al 2008	5 - 15		20 - 337		14 - 74		0 - 1		8 - 27		Beach et al 2015; Griscom et al 2020
		Econ	100 (30 - 635)	247 (20 - 526		4 - 14	16.7 (0 - 100.4)	17 - 304	143.6 (5.7 - 247.4)	7 - 67	64.4 (12.2 - 97.3)	0 - 0	5.9 (0.7 - 22.9)	3 - 25	16.1 (0.9 - 57.8)	
Bioenergy																

BECCS	Bioenergy is the use of biomass to produce energy which can reduce GHGs by displacing the use of fossil fuels in the production of heat, electricity, and fuels. When bioenergy is combined with carbon capture and storage (BECCS), it has the potential to remove carbon by permanently storing (part of) the biogenic carbon	Tech	5000 (500 - 11300)		Fuss 2018; Hansen et al 2020; Koornneef et al 2012; Koornneef et al 2013; Lenton 2010; Lenton 2014; McLaren 2012; Powell and Lenton 2012; Turner et al 2018	202		697		992		29		470		Hanssen et al 2020
		Econ	1600 (500 - 3500)	576 (1 - 2795		44	58 (0.5 - 484.6)	110	172 (0 - 824.6)	112	215.9 (0 - 842.1)	1	27.9 (0 - 102.9)	233	103.4 (0 - 540.4)	
Demand-side																
Shift to sustainable healthy diets	A shift to sustainable healthy diets (improved human diets that are nutritionally healthy and environmentally and socially sustainable, i.e. reduced consumption of livestock products in overconsuming populations and increased consumption of some food groups in populations where minimum nutritional needs are not met.) reduces emissions from diverted agricultural production and avoided land-use change	Tech	4300 (500 - 8000)		Bajzelj 2014; Dickie et al 2014; Hedenus 2014; Herrero et al 2016; Project Drawdown 2020; Smith et al 2013; Springmann et al 2016; Stehfest et al 2009; Tilman and Clark 2014	304		963		524		119		368		Project Drawdown 2020; Eat Lancet 2019
		Econ				207		609		322		72		224		
Reduce food loss and waste	Reducing food loss (post-harvest losses due to limitations in agricultural infrastructure, storage and packaging) and food waste (discarded food in distribution, retail, food service and consumption) reduces emissions from diverted agricultural production and avoided land-use change	Tech	2050 (95 - 5800)		Bajzelj 2014; Dickie et al 2014; Hic et al. 2016; Project Drawdown 2020	116		366		199		45		140		Project Drawdown 2020
		Econ				65		192		102		23		71		
Enhance use of wood products	The enhanced use of wood products refers to the fate of harvested wood for material uses and includes storage of carbon in wood products and material substitution when wood is used for building, textiles, or other applications instead of other materials (e.g., concrete, steel) to avoid or reduce emissions associated with the production, use and disposal of the products.	Tech	437 (40 - 3690)		Churkina et al. 2020; Johnston & Radeloff 2019; McLaren 2012; Miner & Gaudreault 2016; Miner 2010; Oliver et al. 2014	5		162		90		12		22		Johnston & Radeloff 2019

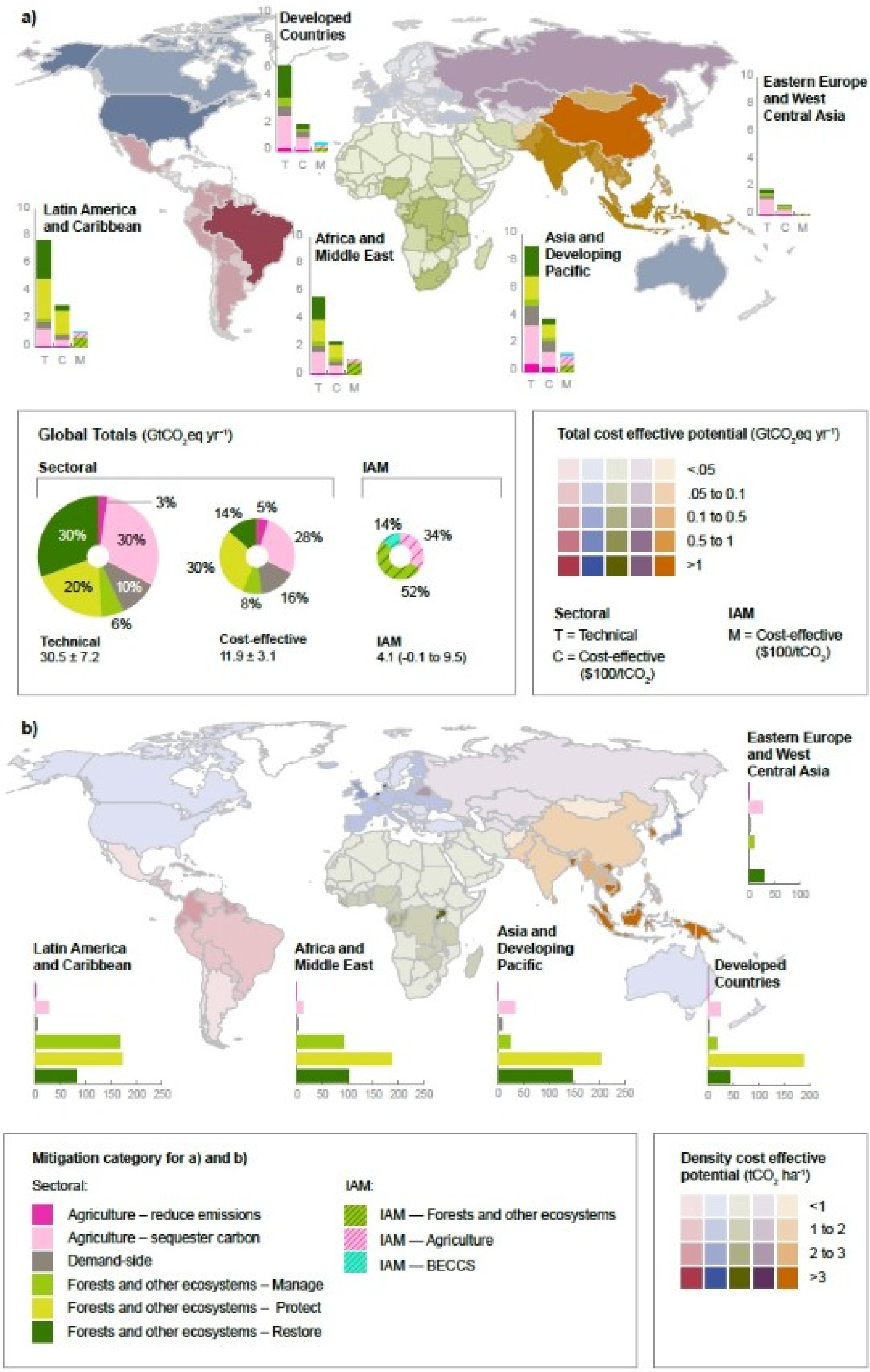


Figure 7.12 Estimated regional mitigation potential in 2020–2050 (references for each measure outlined in Table 7.4). (a) Map of mean economic mitigation potential (available up to USD 100/tCO$_2$-eq), with the five colours corresponding to the five high-level IPCC regions. The bar graphs reflect the mean technical, economic (cost-effective up to USD 100/tCO$_2$-eq) and IAM (up to USD 100/tCO$_2$-eq) mitigation potential by mitigation category. Categories that may overlap were not aggregated (e.g. peatland conversion, BECCS, HWP) to reduce double counting. Due to the different methods and sources used, the regional potentials add up to a slightly different estimate to the global potential ranges in Table 7.4 (b) Map of mean economic mitigation potential density (total potential in a per hectare). The bar graphs reflect the mean densities per mitigation category per region
Source: Roe et al. Under Review).

Table 7.6 Co-benefits and trade-offs in 'Forest and other ecosystem' measures. Readiness (measured by technology readiness level - TRL), potential co-benefits, potential risks and adverse effects, and implementation opportunities (best practices for implementation to maximise co-benefits and reduce risks), by forestry and other ecosystem mitigation measure. Legend for co-benefits and risks: A - Air, B - Biodiversity, C - climate effect, FS - Food security, LD - Land desertification and degradation, R - Resilience and adaptation, RT - resources and technology, SE - Socioeconomic, S - Soil fertility, W - Water.

Mitigation measure	Readiness - TRL	Co-benefits	Risks	Best practices to maximise benefits and reduce risks	References
Forests and other ecosystems					
Reduce deforestation	8-9	A - Improves air quality and reduces pollution B - Preserves ecosystem services and biodiversity FS - Increases yields and land availability R - Enhances adaptation capacity S - Reduces soil erosion, enhances water retention W - Regulates hydrological cycle SE - Enhances employment, incomes, and livelihoods	FS - Limit land used for farming and food production SE - Restrict the rights and access of local people to forest resources; increase dependence to insecure external funding	Conservation of existing carbon pools in forest vegetation and soil by controlling the drivers of deforestation and forest degradation; establish protected areas; improve law enforcement, forest governance and land tenure; support community forest management and forest certification	Alkama & Cescatti, 2016; Baccini et al., 2017; Barlow et al., 2016; Bayrak & Marafa, 2016; Benayas, Newton, Diaz, & Bullock, 2009; Busch & Ferretti-Gallon, 2017; Caplow, Jagger, Lawlor, & Sills, 2011; Curtis, Slay, Harris, Tyukavina, & Hansen, 2018; Dooley & Kartha, 2018; Griscom et al., 2017; Hansen et al., 2013; Hosonuma et al., 2012; Houghton, Byers, & Nassikas, 2015; Lewis, Edwards, & Galbraith, 2015; Pelletier, Gélinas, & Skutsch, 2016
Afforestation and Reforestation	8-9	A - Improves air quality and reduces pollution B - Enhances biodiversity, ecosystem services and connectivity FS - Increases yields and available land R - Enhances adaptation, microclimatic regulation S - Enhances soil quality and reduces erosion, degradation and desertification W - Regulates hydrological cycle SE - Provides renewable resources, increases incomes and livelihoods	C - Change surface albedo (at higher latitudes) and evapotranspiration regime producing a net warming effect B - Loss of biodiversity and ecosystem functions; competition for land FS - At very large scale: Increase food prices through land competition W - Reduce water availability SE - Threatened livelihoods/subsistence agriculture and local land	Accelerating natural regrowth, avoiding conversion of biologically diverse grasslands with plantation monocultures, and consideration of albedo in choice of species (especially at high latitudes)	Alkama & Cescatti, 2016; Arora & Montenegro, 2011; Bonan, 2008; Boysen, Lucht, & Gerten, 2017; Brundu & Richardson, 2016; Cherubini et al. 2017; Ciais et al., 2013; Dooley & Kartha, 2018; Ellison et al., 2017; Findell et al., 2017; Kongsager et al. 2016; Kreidenweis et al., 2016; Lejeune et al. 2018; Li et al., 2015; Locatelli et al., 2015; Medugu, Majid, Johar, & Choji, 2010; Nabuurs et al. 2017; Perugini et al., 2017; Salvati et al. 2014; Smith et al., 2014, 2013;

			access; land use competition and indirect land use change		Stanturf et al., 2015; Verkerk et al 2020
Sustainable forest management	8-9	A - Improves air quality and reduces pollution B - Conserves biodiversity and ecosystem services FS - Improves crop productivity R - Enhances adaptation, microclimatic regulation S - Reduces soil erosion, enhances coastal protection W - Regulates hydrological cycle SE - Enhances employment, incomes, local livelihoods	C - Affect albedo and evapotranspiration B - Decrease in biodiversity in case improved management is seen as short rotations R - Decrease resilience to natural disasters in case improved management is seen as short rotations.	Improved regeneration (natural or artificial) and a better schedule, intensity and execution of operations (thinning, selective logging, final cut, reduced impact logging, Pro Silva type of management, or continuous cover management)	Ashton et al. 2012; D'Amato, Bradford, Fraver, & Palik, 2011; Dooley & Kartha, 2018; Ellison et al., 2017; Erb et al., 2018; Grassi, Pilli, House, Federici, & Kurz, 2018; Griscom et al., 2017; Jantz, Goetz, & Laporte, 2014; Kurz, Smyth, & Lemprière, 2017; Locatelli, 2011; Luyssaert et al., 2018; Nabuurs et al., 2017; Naudts et al., 2016; Pingoud, Ekholm, Sievänen, Huuskonen, & Hynynen, 2018; Putz et al., 2012; Seidl, Schelhaas, Rammer, & Verkerk, 2014; Smith et al., 2014; Smyth et al., 2014; Stanturf et al., 2015; Verkerk et al., 2020
Grassland fire management	8-9	B - Conserves biodiversity in rangelands A - Reduces haze/air pollution FS - Improves productivity, enhanced forage quality R - Improves resilience of grazing lands S - Prevents erosion, desertification, land degradation SE - Improves population health	B - Negative impact on biodiversity	Improved use of fire for sustainable fire management including fire prevention and improved prescribed burning	Archer et al., 2011; Briske et al., 2015; Conant, Cerri, Osborne, & Paustian, 2017; Esteves et al., 2012; FAO, 2006; Herrero et al., 2016; Lin, Wijedasa, & Chisholm, 2017; O'Mara, 2012; Porter et al., 2014; Rulli, Bozzi, Spada, Bocchiola, & Rosso, 2006; Scasta et al., 2016; Schwilch, Liniger, & Hurni, 2014; Seidl, Schelhaas, Rammer, & Verkerk, 2014; Smith et al., 2014; Tacconi, 2016; Tighe,

					Haling, Flavel, & Young, 2012; Valendik, 2011; Westerling, Hidalgo, Cayan, & Swetnam, 2006; Whitehead, Purdon, Russell-Smith, Cooke, & Sutton, 2008; Yong & Peh, 2016
Reduce grasslands and savannas conversion	8-9	A - Improves air quality and reduces pollution B - Preserves ecosystem services and biodiversity FS - Increases yields and land availability R - Enhances adaptation capacity S - Reduces soil erosion, enhances water retention W - Regulates hydrological cycle SE - Enhances employment, incomes, and livelihoods	FS - Limit land used for farming and food production SE - Restrict the rights and access of local people to forest resources; increase dependence to insecure external funding	Conservation of existing carbon pools in savannas and grasslands vegetation and soil by controlling the drivers of conversion and degradation; establish protected areas; improve law enforcement, environmental governance and land tenure; support community land management and certification schemes.	Balima et al., 2020; Baumann et al., 2017; Bristow et al., 2016; de Brito et al., 2019; Estes et al., 2016; Garcia et al., 2017; Li et al., 2020; López-Ricaurte et al., 2017; Naha et al., 2020; Nóbrega et al., 2017; Rausch et al., 2019; Strassburg et al., 2016; Strassburg et al., 2017; van Griensven et al., 2016; Warth et al. 2020
Reduce peatland conversion	8-9	A - Improves air quality and reduces pollution B - Conserves crucial biodiversity, ecosystem services FS - Increases yields and available land R - Enhances adaptation capacity S - Improves soil quality and reduces erosion SE - Improves public health (decreased pollutants); enhances employment, incomes, local livelihoods; enhances employment, incomes, local livelihoods W - Regulates hydrological cycle	FS - Impact farming practices and development SE - Increase competition for other land uses (agriculture, alternative land-based mitigation measures)	Conserve existing carbon pools by controlling drivers of conversion, including logging, drainage, and burning; integrate peatland sensitivity to drainage into land use policies; develop comprehensive management plans to support existing protected area/Ramsar designations; support indigenous land tenure.	Dargie et al., 2019; Lilleskov et al., 2019; Murdiyarso et al., 2019

Peatland restoration	8-9	A - Improves air quality and reduces pollution B - Protects biodiversity and ecosystem services R - Enhances adaptation capacity S - Enhances soil quality, reduces erosion, risks of fire SE - Improves public health (reduces pollutants); enhances employment, incomes, local livelihoods W - Regulates hydrological cycle	C - Increase in methane emissions FS - Displace and damage local food production/supply SE - High initial costs to restore hydrological cycle	For boreal and temperate peatlands: blocking drainage channels; using site appropriate techniques to raise water level to natural condition; removing planted trees; revegetation of bare peat surface; stopping burning; removal of degraded topsoil	Bonn et al., 2016; Nugent et al., 2019; Taillardat et al., 2020; Griscom et al., 2017; Jauhiainen et al., 2008; Limpens et al., 2008; Munang et al., 2014
Reduce mangrove conversion	8-9	A - Improves air quality and reduces pollutions B - Preserves ecosystem services and biodiversity FS - Increases crop yields, land availability, fisheries production R - Enhances adaptation capacity, coastal protection S - Improves soil quality and reduces erosion SE - Enhances employment, incomes, and livelihoods W - Regulates hydrological cycle	C - Potential NH4 emissions FS - Impact farming practices and development SE - Land use competition for urbanisation and infrastructure	Conservation (incl. alleviating stressors); restoration of hydrological flows allowing recolonisation by native mangrove species in fertile soils; revegetation with native plants; livelihood diversification; landscape planning for landward and upstream migration (incl. managed realignment of coastal infrastructure); integrated spatial planning with competing land use	Duarte et al., 2020; Macreadi et al., 2019; Friess et al., 2020; Griscom et al., 2017; Lotze et al., 2006; Munang et al., 2014; Naylor et al., 2000; Chow 2018; Widham-Myers et al., 2018
Mangrove restoration	8-9	A - Improves air quality and reduces pollution B - Enhances biodiversity and habitat FS - Increases yields, available land, fishery productivity R - Increases resilience to natural hazards, SLR, erosion S - Enhances soil quality; reduces erosion, land degradation SE - Enhances employment, incomes, local livelihoods W - Regulates hydrological cycle	FS - Displace and damage local food production/supply SE - Land use competition for urbanisation and infrastructure	Restoring hydrological flows allowing recolonisation by native mangrove species in fertile soils; revegetation with native plants; livelihood diversification; landscape planning for landward and upstream migration (incl. managed realignment of coastal infrastructure); reduce local stressors on seagrasses (industrial sewage, anchoring and trawling regulation).	Duarte et al., 2020; Macreadi et al., 2019; Friess et al., 2020; de los Santos et al., 2019; Griscom et al., 2017; Lotze et al., 2006; Munang et al., 2014; Naylor et al., 2000

Table 7.7 Co-benefits and trade-offs in Agriculture measures. Readiness (measured by technology readiness level - TRL), potential co-benefits, potential risks and adverse effects, and implementation opportunities (best practices for implementation to maximise co-benefits and reduce risks), by forestry and other ecosystem mitigation measure. Legend for co-benefits and risks: A - Air, AW – Animal Welfare, B - Biodiversity, C - climate effect, FS - Food security, LD - Land desertification and degradation, R - Resilience and adaptation, RT - resources and technology, SE - Socioeconomic, S - Soil fertility, W - Water.

Mitigation measure	Readiness - TRL	Co-benefits	Risks	Best practices to maximise benefits and reduce risks	References
Agriculture					
Soil organic carbon in croplands and grasslands	8-9	A - Improves air quality and reduces pollutions B - Improves biodiversity FS - Increases yields and available land R - Enhances adaptation capacity S - Improves soil quality and function W - Regulates hydrological cycle SE - Enhances employment and incomes	C - Increase in nitrogen input offsetting soil organic carbon sequestration RT - Difficulty in monitoring and verification	In croplands: ensuring optimal design of crop rotations, (that potentially include cover crops, green manures or catch crops), tillage operations and nutrient management to suit specific cropping systems and spoil types. In grassland: ensuring appropriate nutrient management and optimal stocking rates that are in line with the carrying capacity of the land and ensure sufficient, but not over-grazing of swards, with avoidance of soil compaction from livestock poaching/pugging or machinery operations vital. In all cases, knowledge exchange programs and farm extension or advisory services are crucial in supporting information dissemination and appropriate on-farm management.	Smith et al., 2016, 2020; Lehmann, Bossio, Kögel-Knabner & Rillig, 2020
Agroforestry	8-9	A - Improves air quality and reduces pollution B - Increases biodiversity and perennial vegetation FS - Enhances land productivity R - Enhances adaptation capacity and microclimatic regulation, and reduces vulnerability S - Improves soil quality, reduces	B - Disturbs native ecosystem W - Change local hydrology; water requirements S - Soil, seed and germplasm requirements SE - Social inequality; limited farmer agency, access to credit and information on	Increase carbon in agricultural landscapes by supporting the planting and natural regeneration of trees on farms and ranches by reforming policy; developing and delivering adapted germplasm; strengthening information systems; creating market opportunities for tree products.	Antwi-Agyei, Stringer, & Dougill, 2014; Benjamin, Ola, & Buchenrieder, 2018; den Herder et al., 2017; Ellison et al., 2017; Guo, Wang, Wang, Wu, & Cao, 2018; Mbow et al., 2014; Mosquera-Losada et al., 2018; Mutuo, Cadisch, Albrecht, Palm, & Verchot, 2005; Nair & Nair,

		nutrient leakage and erosion, restores degraded lands, reduces frequency and/or severity of dust storms SE - Enhances employment, incomes and diversified local livelihoods; source of micronutrients; enables payments to farmers for ecosystem services W - Regulates hydrological cycles	implementation may hinder implementation		2014; Ram et al., 2017; Rosenstock et al., 2014; Sain et al., 2017; Santiago-Freijanes et al., 2018; Sida, Baudron, Hadgu, Derero, & Giller, 2018; Vignola et al., 2015; Yirdaw, Tigabu, & Monge, 2017; Kuyah et al., 2019; Mbow et al., 2020; Holl and Brancalion, 2020; Kay et al., 2019; Muchane et al., 2019; Bargues-Torbella et al., 2019
Biochar from crop residues	6-7	A - Improves air quality and reduces pollution B - Improves soil biodiversity, balances forest fuel loads and reduces wildfire risks FS - Increases yields, available land, nitrogen use efficiency R - Enhances resilience to drought S -Reduces erosion, improves soil quality , and enhances soil functions (reduce nutrient runoff and leaching , enhanced nitrogen fixation, reduced availability of organic pollutants and heavy metals, reduced environmental contamination W - Regulates hydrological cycle SE - Odor reduction (manure handling and application); enhances employment and incomes	C - Decrease soil albedo (not significant under recommended rates and application methods) B - Biodiversity and carbon stock loss if biomass crops replace natural lands; competition for biomass resources SE - Limited large-scale production facilities, experience, knowledge, standardisation and quality control, leading to lack of confidence; high production costs (at small scale)	As biochar properties vary widely according to feedstock and production conditions, biochar should be carefully selected that suit the application context, including geo-physical and climatic factors, to optimise mitigation outcomes and production co-benefits. Application at recommended rates and soil incorporation, can prevent potential soil albedo impacts.	Puettman et al., 2020; Woolf et al., 2016; Jeffery et al., 2017; Hwang et al., 2018; Omondi et al., 2016; Liu et al., 2019; Borchard et al., 2019; Van Zwieten et al., 2015; Silvani et al., 2019; Gwenzi et al., 2015
Enteric fermentation	6-7	A - Improves air quality and reduces pollution AW – Improved animal welfare FS - Increased animal productivity	SE - High technology, capacity and financial needs of farmers to implement AW- Toxicity and animal welfare issues B, C & LD- Land use change	Some measures are well established and should be implemented according to current farming system as appropriate. Knowledge exchanges programs and farm extension or advisory services are crucial in supporting information dissemination	

			from increased production of feed	and appropriate on-farm management. Further research is required into specific measures, and notably regarding potential mitigation persistence, toxicity and administration best practice.	
Manure management	6-7	A - Improves air quality and reduces pollution FS - Increases yields and available land R - Enhances adaptation capacity, system resilience S - Improves soil quality, reduces erosion, degradation W - Reduce water pollution and eutrophication SE - Enhances employment and incomes	C - Risk of methane slip and increased N2O emissions FS - Reduce yields SE - High technology, capacity and financial needs of farmers to implement	Digestate as soil amendment, manipulation of bedding and storage conditions, anaerobic digesters; biofilters, dietary change and additives, soil-applied and animal-fed nitrification inhibitors, urease inhibitors, fertiliser type, rate and timing, manipulation of manure application practices and grazing management	Archer et al., 2011; Herrero et al., 2016; Miao et al., 2015; Porter et al., 2014; Rojas-Downing, Nejadhashemi, Harrigan, & Woznicki, 2017; Smith et al., 2014, 2008; Squires & Karami, 2015; Tighe, Haling, Flavel, & Young, 2012; Smith et al. 2019, Mbow et al. 2019
Nutrient management	7-8	A - Improves air quality and reduces pollution FS - Improves yields, land availability, water efficiency use R - Enhances adaptation capacity S - Improves soil quality and reduces erosion W - Reduce water pollution and eutrophication SE - Enhances employment and incomes	FS - Reduce yields SE - High technology, capacity and financial needs of farmers to implement	Basic soil testing and the development of nutrient management plans where possible, will greatly aid improved crop nutrient management. The integration of multiple approaches, including utilisation of different forms of manures, nitrogen fixing crops and synthetic fertilisers, or both high- and low-tech precision fertiliser application methods.	
Rice cultivation	7-8	A - Improves air quality and reduces pollution FS - Increases yields and available land R - Enhances adaptation capacity S - Improves soil quality and reduces erosion W - reduce water use and pollution SE - Enhances employment and incomes	FS - Reduce yields SE - High technology, capacity and financial needs of farmers to implement	Water management such as mid-season drainage and improved fertilisation and residue management in paddy rice systems. As with all agricultural measures, effective knowledge exchanges programs and farm extension or advisory services are crucial for information dissemination and on-farm management support.	Bryan, Deressa, Gbetibouo, & Ringler, 2009; Chen et al., 2019; Labrière, Locatelli, Laumonier, Freycon, & Bernoux, 2015; Lal, 2011; Poeplau & Don, 2015; Porter et al., 2014; Smith et al., 2014; Tilman, Balzer, Hill, & Befort, 2011; Smith 2008b

Table 7.8 Co-benefits and trade-offs in 'Demand-side' measures. Readiness (measured by technology readiness level - TRL), potential co-benefits, potential risks and adverse effects, and implementation opportunities (best practices for implementation to maximise co-benefits and reduce risks), by forestry and other ecosystem mitigation measure. Legend for co-benefits and risks: A - Air, B - Biodiversity, C - climate effect, FS - Food security, LD - Land desertification and degradation, R - Resilience and adaptation, RT - resources and technology, SE - Socioeconomic, S - Soil fertility, W - Water.

Mitigation measure	Readiness - TRL	Co-benefits	Risks	Best practices to maximise benefits and reduce risks	References
Demand-side					
Shift to sustainable, healthy diets	6-7	A - Improves air quality and reduces pollution B - Reduces pressure on forests, protecting biodiversity FS - Decreases production intensity and use of inputs SE - Improves population health, prevents malnutrition	FS - Shift to unsustainable fisheries SE- Reduce farmers' incomes	Contract and converge model of transition to sustainable healthy diets: reduction in over-consumption (esp. livestock products) in pop., increased consumption of some food groups in pop. where minimum nutritional needs are not met, resulting in a decline in undernourishment, risk of morbidity and mortality due to over-consumption	Aleksandrowicz, Green, Joy, Smith, & Haines, 2016; Bajželj et al., 2014; Bonsch et al., 2016; Erb et al., 2016; Godfray et al., 2010; Haberl et al., 2011; Havlík et al., 2014; Muller et al., 2017; Roe et al., 2019; Smith et al., 2013; Springmann et al., 2018; Stehfest et al., 2009; Tilman & Clark, 2014; Wu et al., 2019; FAO 2018
Reduce food waste	6-7	A - Improves air quality and reduces pollution B – Reduces need for agricultural land, protects biodiversity FS - Increases food availability; decreases use of inputs, pressure on (crop)land, and reduces food costs SE - Enhances employment, incomes, and livelihoods	R - Susceptibility to temperature increases SE - Short-term profit shortfalls for retailers	Cold chains for preservation; processing for value addition and linkages to value chains that absorb the harvests almost instantly into the supply chain; improve and expand the "dry chain"	Alexander, Brown, Arneth, Finnigan, & Rounsevell, 2016; Ansah, Tetteh, & Donkoh, 2017; Bajželj et al., 2014; Billen et al., 2019; Bradford et al., 2018; Chaboud & Daviron, 2017; Göbel, Langen, Blumenthal, Teitscheid, & Ritter, 2015; Ingram et al., 2016; Kissinger, Sussmann, Dorward, & Mullinix, 2019; Kumar & Kalita, 2017; Kummu et al., 2012; Muller et al., 2017; Ritzema et al., 2017; Roe et al., 2019; Sheahan & Barrett, 2017; Smith et al., 2013; Vermeulen, Campbell, & Ingram, 2012; Wilhelm, Blome, Bhakoo, & Paulraj, 2016

Enhance wood products	8-9	A - Reduces pollution B - Conserves biodiversity and ecosystem services R – Provides opportunity to enhance resilience of forests and adaptation SE - Provides rural development opportunities, contributes to renewable resource management, adds value to land $ - Enhances employment, incomes, and livelihoods	B - Decrease in biodiversity LD - Degradation through unsustainable wood production systems W – Risk for eutrophication of water bodies		Chaudhary et al., 2016; Weiss et al., 2012; Baumgartner, 2017; Verkerk et al., 2020; Kastner et al., 2011; Pendrill et al., 2019.

Box 7.2 Useful definitions relating to mitigation measures

Afforestation: The conversion to forest of land that historically has not contained forests.

Agroecology: *As defined by the SRCCL (IPCC 2019)* 'The science and practice of applying ecological concepts, principles and knowledge (i.e., the interactions of, and explanations for, the diversity, abundance and activities of organisms) to the study, design and management of sustainable agroecosystems. It includes the roles of human beings as a central organism in agroecology by way of social and economic processes in farming systems. Agroecology examines the roles and interactions among all relevant biophysical, technical and socioeconomic components of farming systems and their surrounding landscapes' (IPBES 2019)

Carbon dioxide removal (CDR): Measures that result in a net removal of GHGs from the atmosphere and storage in living or dead organic material, or in geological stores. CDR is also frequently referred to in the literature as greenhouse gas removal (GGR) or negative emissions technologies (NETs).

Climate-smart agriculture (CSA): An approach to agriculture that aims to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/ or removing greenhouse gas emissions, where possible (see Box 7.6 on the climate-smart village approach).

Conservation Agriculture: The combined use of minimum tillage, crop rotations (including cover crops) and residue retention (Jia et al. 2019) to ensure minimal soil disturbance and maintained soil cover (Mbow et al. 2019; Mirzabaev et al. 2019).

Enteric Fermentation: A natural part of the digestion process in ruminant animals such as cattle (*Bos indicus and Bos Taurus*) and sheep (*Ovis aries*). Microorganisms (bacteria, archaea, fungi, protozoa and viruses) present in the fore-stomach (reticulorumen or rumen) breakdown plant biomass to produce substrates that can be used by the animal for energy and growth with methane produced as a by-product. Fermentation end-products such as hydrogen, carbon dioxide, formate and methyl-containing compounds are important substrates for the production of methane by the rumen's methane-forming archaea (known as methanogens).

Nature-based Solutions: Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (IUCN, 2016)

Net negative emissions: A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases (GHG) are removed from the atmosphere than are emitted into it.

Organic Farming: An agricultural production system that utilises natural processes and cycles to limit off-farm and notably synthetic inputs, while also aiming to enhance agroecosystems and society. Organic farming is often legally defined and governed by standards, typically guided by principles outlined by the International Federation of Organic Agriculture Movements (Tuomisto et al. 2012; IFOAM 2017).

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

Sustainable Intensification (of agriculture): *As defined by the SRCCL (IPCC 2019)* Increasing yields from the same area of land while decreasing negative environmental impacts of agricultural production and increasing the provision of environmental services (CGIAR 2019). [Note: this definition is based on the concept of meeting demand from a finite land area, but it is scale dependent. Sustainable intensification at a given scale (e.g. global or national) may require a decrease in production intensity at smaller scales and in particular places (often associated with previous, unsustainable, intensification) to achieve sustainability (Garnett et al. 2013).]

Reducing Emissions from Deforestation and Forest Degradation (REDD+): Refers to reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks

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

Regenerative Agriculture: A universally agreed definition of this relatively new approach has yet to be established, but it broadly refers to the implementation of varying combinations of context specific agricultural management practices, to ensure the continued restoration and enhancement of soil health, biodiversity and ecosystem functioning, in conjunction with profitable agricultural production (Francis et al. 1986; Rhodes 2017; Teague 2018; La Canne and Lundgren 2018; Elevitch et al. 2018; Colley et al. 2019; Gosnell et al. 2019).

7.4.2 Forests and other ecosystems

7.4.2.1 Reduce deforestation and degradation

Activities, co-benefits, risks and implementation opportunities and barriers. Reducing deforestation and forest degradation conserves existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance. Forest carbon pools can be conserved by controlling the drivers of deforestation (i.e. commercial and subsistence agriculture, mining, urban expansion) and forest degradation (i.e. overharvesting including fuelwood collection, poor harvesting practices, overgrazing, pest outbreaks, and extreme wildfires), as well as by establishing protected areas, improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification (Smith et al. 2014; Smith et al. 2019). Reducing deforestation provides numerous co-benefits, preserving biodiversity and ecosystem services (e.g. air and water filtration, water cycling, nutrient cycling) more effectively and at lower costs than afforestation/reforestation (Jia et al. 2019:). Potential adverse side effects from efforts to reduce deforestation and forest degradation include reducing the availability of land for farming, displacement of emissions, restricting the rights and access of local people to forest resources, or increasing the dependence of local people to insecure external funding. Barriers to implementation include unclear land tenure, weak environmental governance, insufficient funds, and increasing pressures associated to agriculture conversion, resource exploitation and infrastructure development (Sections 7.3 and 7.6).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Reducing deforestation and forest degradation represents one of the most effective options for climate change mitigation, with technical potential estimated at 0.4–5.8 $GtCO_2\ yr^{-1}$ by 2050 (*high confidence*) (SRCCL, Chapters 2 and 4, and Table 6.14). The higher technical estimate represents a complete halting of land use conversion in forests and peatland forests (i.e., assuming recent rates of carbon loss are saved each year) and includes vegetation and soil carbon pools. Due to the combined climate impacts of GHGs and biophysical effects, reducing deforestation in the tropics has a major climate mitigation effect (SRCCL, Chapter 2). The IPCC AR5 report included estimates of economic potentials from sectoral regional studies and integrated assessments (that produced higher values). Ranges of economic potentials for forestry ranged from 0.01 – 1.45 $GtCO_2\ yr^{-1}$ for USD 20/tCO_2 to 0.2 – 13.8 $GtCO_2\ yr^{-1}$ for USD 100/tCO_2 by 2030 with reduced deforestation dominating the forestry mitigation potential LAM and MAF, but very little potential in OECD-1990 and EIT (IPCC AR5).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, several studies have provided updated and convergent estimates of economic mitigation potentials by region (Busch et al. 2019; Griscom et al. 2020; Austin et al. 2020). Tropical forests and /savannas in Latin America provide the largest share of mitigation potential (3.9 $GtCO_2$ yr^{-1} technical, 2.5 $GtCO_2$ yr^{-1} at USD 100/tCO_2) followed by Southeast Asia (2.2 $GtCO_2$ yr^{-1} technical, 1.5 $GtCO_2$ yr^{-1} at USD 100/tCO_2) and Africa (2.2 $GtCO_2$ yr^{-1} technical, 1.2 $GtCO_2$ yr^{-1} at USD 100/tCO_2) (Table 7.5). Tropical forests continue to account for the highest rates of deforestation and associated GHG emissions. While deforestation shows signs of decreasing in several countries, in others, it continues at a high rate or is increasing (Turubanova et al. 2018). Between 2010-2020, the rate of net forest loss was 4.7 Mha yr^{-1} with Africa and South America presenting the largest shares (3.9 Mha and 2.6 Mha, respectively) (FAO 2020).

A major uncertainty in all studies on avoided deforestation potential is their reliance on future reference levels that vary across studies and approaches. If food demand increases in the future, for example, the area of land deforested will likely increase, suggesting more technical potential for avoiding deforestation. Transboundary leakage due to market adjustments could also increase costs or reduce effectiveness of avoiding deforestation (e.g. Ingalls et al. 2018; Gingrich et al. 2019), however, economic studies have generally not found large estimates of leakage in projects that reduce deforestation thus far (Fortmann et al. 2017; Roopsind et al. 2019). Regarding forest regrowth, there are uncertainties about the time for the secondary forest carbon saturation (Houghton and Nassikas, 2017; Zhu et al. 2018). Also, the drivers of forest changes vary regionally, associated with differing mechanisms as expansion or contraction of forests, with further loss of area to wildfire; and changes in vegetation productivity. Additionally, permanence of avoided deforestation may also be a concern due to the impacts of climate change and disturbance of other biogeochemical cycles on the world's forests that can result in future potential changes in terrestrial ecosystem productivity, climate-driven vegetation migration, wildfires, forest regrowth and carbon dynamics (Ballantyne et al. 2012; Kim et al. 2017; Aragão et al. 2018; Lovejoy and Nobre 2018).

Critical assessment and conclusion. Studies since the last IPCC reports indicate the technical mitigation potential for reducing deforestation and degradation is significant, particularly for tropical forests (Latin America, Southeast Asia, and Africa) where mitigation estimates range from 2.2 - 3.9 $GtCO_2$ yr^{-1} per region. Over the last decade, hundreds of subnational initiatives that aim to reduce deforestation related emissions have been implemented across the tropics (see Section 7.6). Reduced deforestation is a central piece of the NDCs in the Paris Agreement (Seddon et al. 2019) and keeping the temperature below 1.5°C (Crusius 2020). Conservation of forests provides multiple co-benefits linked to ecosystem services, biodiversity and sustainable development (see Section 7.6.). Still, ensuring good governance, accountability (e.g. enhanced monitoring and verification capacity; Bos 2020), and the rule of law are crucial for implementing forest-based mitigation options. In many countries with the highest deforestation rates, insecure land rights often are significant barriers for forest-based mitigation options (Gren and Aklilu, 2016; Essl et al. 2018).

7.4.2.2 Afforestation, reforestation and forest ecosystem restoration

Activities, co-benefits, risks and implementation opportunities and barriers. Afforestation and reforestation (A/R) are activities that convert land to forest, where reforestation is on land that has previously contained forests, while afforestation is on land that historically has not been forested (Box 7.2). Forest restoration refers to a form of reforestation that gives more priority to ecological integrity as well, even though it can still be a managed forest. Depending on the location, scale, and choice and management of tree species, A/R activities have a wide variety of co-benefits and trade-offs. Well-planned, sustainable reforestation and forest restoration can enhance climate resilience and biodiversity, and provide a variety of ecosystem services including water regulation, microclimatic regulation, soil erosion protection, as well as renewable resources, income and livelihoods (Ellison et al 2017; Stanturf et al. 2015; Locatelli et al. 2015; Verkerk et al. 2020). Afforestation, when well planned, can help address land degradation and desertification by reducing runoff and erosion and lead to cloud formation however, when not well planned, there are localised trade-offs such as reduced water yield or biodiversity (Teuling et al. 2017; Ellison et al. 2017). The use of non-native species and monocultures may have adverse impacts on ecosystem structure and function, and water availability, particularly in dry regions (Ellison et al. 2017). A/R activities may change the surface albedo and evapotranspiration regimes, producing net cooling in the tropical and subtropical latitudes for local and global climate and net warming at high latitudes (Section 7.4.2). Large-scale implementation of A/R may negatively affect food security since an increase in global forest area can increase food prices through land competition (Smith et al. 2018; Kreidenweis et al. 2016).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 did not provide a new specification of A/R potential, but referred to AR4 mostly for forestry measures (Nabuurs et al. 2007). AR5 did view the feasible A/R potential from a diets change scenario that released land for reforestation and bioenergy crops. AR 5 provided top-down estimates of costs and potentials for forestry mitigation options - including reduced deforestation, forest management, afforestation, and agroforestry, estimated to contribute between 1.27 and 4.23 $GtCO_2$ yr^{-1} of economically viable abatement in 2030 at carbon prices up to 100 USD/t CO_2-eq (Smith et al. 2014).

The SRCCL remained with a reported wide range of mitigation potential for A/R of 0.5–10.1 $GtCO_2$ yr^{-1} by 2050 (*medium confidence*) (SRCCL Ch 2 and Ch 6; Roe et al. 2019; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Kreidenweis et al. 2016; Li et al. 2016; Huang et al. 2017). The mitigation section in SRCCL is short and generally provides global ranges of estimates based on Roe et al. (2019). The higher estimate represents a technical potential of reforesting all areas where forests are the native cover type (reforestation), constrained by food security and biodiversity considerations, considering above and below-ground carbon pools and implementation on a rather theoretical maximum of 678 Mha of land (Griscom et al. 2017). The lower estimates represent the minimum range from an Earth System Model (Yan et al. 2017) and a sustainable global negative emissions potential (Fuss et al. 2018). Climate change will affect the mitigation potential of reforestation due to impacts in forest growth and composition, as well as changes in disturbances including fire. However, none of the mitigation estimates included in the SRCCL account for climate impacts.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since SRCCL, additional studies have been published on A/R mitigation potential by Bastin et al. (2019), Lewis et al. (2019), Doelman et al (2019), Favero et al. (2020) and Austin et al. (2020). These studies are within the range reported in the SRCCL stretching the potentials at the higher range. The rising public interest in nature-based solutions, along with high profile initiatives being launched (UN Decade on Restoration announced in 2019, the Bonn challenge on 150 million ha of restored forest in 2020 and e.g. the trillion-tree campaign launched by the World Economic Forum in 2020), has prompted intense discussions on the scale, effectiveness, and pitfalls of A/R and tree planting for climate mitigation (Anderegg et al 2020; Holl et al. 2020; Heilmayr et al. 2020; Hong et al. 2020; Bond et al. 2019; Luyssaert et al 2018). The sometimes sole attention on afforestation and reforestation suggesting it may solve the climate problem to large extent in combination with the very high estimates of potentials have led to polarisation in the debate, again resulting in a push back to nature restoration only (Lewis and Wheeler 2019).

Our assessment based on most recent literature produced regional economic mitigation potential at USD 100/tCO_2 estimate of 100-400 $MtCO_2$ yr^{-1} in Africa, 210-266 $MtCO_2$ yr^{-1} in Asia and developing Pacific, 291 $MtCO_2$-eq yr^{-1} in Developed countries (87% in North America), 30 $MtCO_2$-eq yr^{-1} in Eastern Europe and West-Central Asia, and 345-898 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean (Table 7.5), which totals to about 1200 $MtCO_2$ yr^{-1}, leaning to the lower range of the potentials in earlier IPCC reports. A recent global assessment of the aggregate costs for afforestation and reforestation suggests that at USD 100/tCO_2, 1.6 $GtCO_2$ yr^{-1} could be sequestered globally for an annual cost of USD130 billion (Austin et al. 2020). Sectoral studies that are able to deal with local circumstances and limits estimate A/R potentials at 20 $MtCO_2$ yr^{-1} in Russia (Eastern Europe and West-Central Asia) (Romanovskaya et al. 2019) and 64 $MtCO_2$ yr^{-1} in Europe (Nabuurs et al. 2017). Domke et al. (2020) estimated for the United States an additional 20% sequestration rate from tree planting to achieve full stocking capacity of all understocked productive forestland, in total reaching 187 $MtCO_2$ yr^{-1} sequestration. A new study on costs in the United States estimates 72-91 $MtCO_2$ yr^{-1} could be sequestered between now and 2050 for USD 100/t CO_2 (Wade et al. 2019). The tropical and subtropical latitudes are the most effective for forest restoration in terms of carbon sequestration because of the rapid growth and lower albedo of the land surface compared with high latitudes (Lewis et al. 2019). While albedo is widely recognised as important (Section 7.2.4), its effects on costs and potentials are not widely known, however, a recent study has estimated that costs may be 46% greater if albedo is considered in North America, Russia, and Africa (Favero et al., 2018). A review of 154 ongoing and planned restoration projects in Latin America and the Caribbean indicated that most projects occur in the humid tropics, and drylands receive less attention (Romijn et al. 2019).

Estimates of carbon sequestration per unit area are still uncertain and have large ranges. The uncertainty is due to the scarcity of large-scale restoration especially on degraded sites (see also Box 7.13), the many different land characteristics available for restoration, and the various restoration activities (Wheeler 2016). The rate of aboveground carbon sequestration of naturally regenerating forests was estimated as 2.5 Mg C ha^{-1} yr^{-1} (± 0.6, 95% CI) over 100 years, independent of prior land use (n = 71 studies) (Wheeler 2016). A regional study quantifying natural and assisted regeneration in 240 Mha of second-growth tropical forest in Latin America showed sequestration of 8.48 Pg C in aboveground biomass over 40 years, or 0.8 Mg C ha^{-1} yr^{-1} (Chazdon 2016). In addition, a wide variety of sequestration rates have been collected and published in e.g. IPCC Good Practice Guidance for the AFOLU sector (IPCC 2006).

Critical assessment and conclusion. The global economic mitigation potential (<USD 100/tCO_2) of afforestation and reforestation activities is approximately 1.2 ±0.4 GtCO2 yr^{-1} (requiring about 200 Mha). Per hectare a long (~100 year) sustained effect of 5-10 tCO_2 ha^{-1} yr^{-1} is realistic with ranges between 1-20 tCO_2 ha^{-1} yr^{-1}. Not all sectoral studies rely on economic models that account for leakage, which may be > 50% (Murray et al. 2004; Sohngen and Brown 2004), suggesting that technical potential may be overestimated.

7.4.2.3 Improved forest management

Activities, co-benefits, risks and implementation opportunities and barriers. Sustainable forest management (SFM) is the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems (IPCC SRCCL, Chapter 6). Climate change will likely affect the mitigation potential of forest management due to shifts in forest growth, as well as changes in disturbances including fire, insects and pathogens. On the other hand, improved management can also partially prevent and counteract the impacts of disturbances, and can lead to higher forest carbon stocks, better quality of produced wood and continuously produce wood while maintaining and enhancing the forest carbon stock (Seidl et al. 2017; Kurz et al 2008; Marlon et al., 2012; Abatzoglou and Williams, 2016; Tian et al., 2018; Hashida et al. 2020; Nabuurs et al, 2017).

Improved management can provide benefits for climate change mitigation, adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection, coastal area protection and water and flood regulation (Ashton et al. 2012, Verkerk et al. 2020). Often, results will be subtle and mitigation strategies effects should to be assessed only in conjunction with the overall forest and wood use system, i.e., carbon stock changes in standing trees, soil, harvested wood products (HWPs) and its bioenergy component with the avoided emissions through substitution. The net carbon emissions should then be assessed against a baseline. Forest management strategies aimed solely at increasing the biomass stock may have adverse side effects, such as decreasing the stand-level structural complexity, biodiversity and resilience to natural disasters, although strict reserves are certainly needed for biodiversity conservation. Forest management also affects albedo and evapotranspiration although the net result is unclear with small changes in management (Section 7.2.4).

Under current climate, mitigation options for forest management will vary widely, depending on the forest owner, the biophysical circumstances, as well as regional wood markets and local communities. Further, there is a trade-off between management in various parts of the forest product value chain, resulting in a wide range of results on the role of managed forests in mitigation (Agostini et al., 2013; Braun et al., 2016, Gustavsson et al. 2017. Erb et al, 2017, Soimakallio et al. 2016, Hurmekoski et al. 2020, Favero et al. 2020) and where managed forests do not necessarily contain less carbon than unmanaged systems, and when the whole value chain is regarded, carbon storage may be quite similar (Schulze et al 2019, DenOuden et al. 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL, forest management activities have the potential to mitigate 0.4–2.1 $GtCO_2$-eq yr^{-1} by 2050 (*medium confidence*) (SRCCL: Griscom et al, 2017; Roe et al. 2019). The higher estimate stems from assumptions of applications on roughly 1.9 billion ha of already managed forest. It combines both natural forest management as well as improved plantations, on average with a small net additional effect per hectare, not including substitution effects in the energy sector nor the buildings sector.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, the Forest Resources Assessment 2020 was released. The assessment finds that more than 2 billion ha of forests currently have management plans (FRA, 2020) and the overall growing stock in the world's forests is increasing. The regional distribution is unequal with most of European forests (including Russia) being under management plans, while management plans exist for less than 25% of forests in Africa and less than 20 % in South America. Nevertheless, the area of forest under management plans has increased in all regions since 2000 by 233 Mha (FRA, 2020). The roughly 1 billion ha of secondary and degraded forests would be ideal to invest in and develop a sustainable sector that pays attention to biodiversity, wood provision and climate mitigation at the same time. This all depends on the effort made, the development of expertise, know-how in the field, nurseries with adapted provenances, etc as was also found for Russian climate smart forestry options (Leskinen et al. 2020) .

Regionally, recently updated economic mitigation potential at USD 100/tCO_2 have 179-186 $MtCO_2$-eq yr^{-1} in Africa, 193-313 $MtCO_2$-eq yr^{-1} in Asia and developing Pacific, 215-220 $MtCO_2$-eq yr^{-1} in Developed countries , 82-152 $MtCO_2$-eq yr^{-1} in Eastern Europe and West-Central Asia, and 62-204 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean (Table 7.5). Additional ad hoc regional studies (with a variation of what is included) specify the potentials as follows. In Russia, where there are large areas of intact and remote forests, Romanovskaya et al (2019) estimate the potential of forest fires management at 220–420 $MtCO_2$ yr^{-1}, gentle logging technology at 15–59, reduction of wood losses at 61–76, and improved reforestation (replace conifer monocultures with mixed stands) at 50–70 $MtCO_2$ yr^{-1}, or a total of 346 – 625 $MtCO_2$ yr^{-1}, higher than the updated regional potential for Eastern Europe and West-Central Asia. In North America, Austin et al. (2020) estimate that in the next 30 years, forest management could contribute 154 $MtCO_2$ yr^{-1} in the US and Canada with 81 $MtCO_2$ yr^{-1} available at less than USD100 per ton. In Canada, the largest share of the increase in carbon from management is due to extending the optimal time to harvest trees, including reducing harvests in some remote regions (Austin et al., 2020). In one production region (British Columbia) a cost-effective portfolio of scenarios was simulated that directed more of the harvested wood to longer-lived wood products, stopped burning of harvest residues and instead produced bioenergy to displace fossil fuel burning, and reduced harvest levels in regions with low disturbance rates. Net GHG emissions were reduced by an average of -9

$MtCO_2$-eq yr^{-1} (Smyth et al. 2020). In Europe, climate smart forestry could mitigate 0.19 $GtCO_2$ yr^{-1} by 2050 (Nabuurs et al. 2017), in line with the regional estimates in Table 7.5. For the US results are consistent with a new economic analysis that estimates 99-141 $MtCO_2$ yr^{-1} from forest management at USD 100/tCO_2 (Wade et al., 2019). In China, forest stocks increased by 600 $MtCO_2$-eq yr^{-1} from 2001-2010 (Fang et al., 2018), and project-induced forest management efforts (including reducing harvests) contributed 126 $MtCO_2$-eq yr^{-1} from 2001-2010 (Lu et al., 2018). An additional 105 Mton yr-1 could be obtained through additional management activities for less than USD 100/tCO_2 (Austin et al., 2020).

In the tropics, estimates of the pantropical climate mitigation potential of natural forest management (a light intensity management in secondary forests), across three tropical regions (Latin America, Africa, Asia), is around 0.66 $GtCO_2$-eq yr^{-1} with Asia responding for the largest share followed by Africa and Latin America (Table 7.5). Selective logging occurs in at least 20% of the world's tropical forests and causes at least half of the emissions from tropical forest degradation (Asner et al., 2005, Blaser and Kuchli 2011; Pearson et al. 2017). Reduced-impact logging for climate (RIL-C; promotion of reduced wood waste, narrower haul roads, and lower impact skidding equipment)) has the potential to reduce logging emissions by 44% (Ellis et al. 2019), while also providing timber production.

Critical assessment and conclusion. Efforts to change forest management require good skilled labour, good access etc. These requirements already outline that although the potential is of medium size, we estimate a feasible potential towards the lower end. The net effect is also difficult to assess, as management changes impact not only the forest biomass, but also the wood chain and substitution effects. Further, leakage can arise from efforts to increase management for carbon sequestration. Efforts e.g. to set aside large areas of forest, maybe partly counteracted by higher harvesting pressures elsewhere (Kallio and Solberg 2018). studies such as Austin et al. (2020) implicitly account for leakage and thus suggest higher costs than other studies. We therefore judge the mitigation potential at medium certainty and *medium confidence*.

Box 7.3 Case study: Climate Smart Forestry in Europe

Summary

European forests have been regarded as prospering and increasing for the last 5 decades. However, these views also changed recently. Climate change is putting a large pressure on Norway spruce stocks in Central Europe (Nabuurs et al. 2019) with estimates of mortality reaching 200 million m^3, biodiversity under pressure, the Mediterranean area showing a weak sector and harvesting pressure in the Baltics and north reaching maxima achievable. A European strategy for unlocking the EU's forests and forest sector potential was needed and was based on the concept of "Climate Smart Forestry" (CSF) (Nabuurs et al. 2017, Verkerk et al. 2020).

Background

The idea behind CSF is that it considers the whole value chain from forest to wood products and energy, illustrating that a wide range of measures can be applied to provide positive incentives for more firmly integrating climate objectives into the forest and forest sector framework. CSF is more than just storing carbon in forest ecosystems; it builds upon three main objectives; (i) reducing and/or removing greenhouse gas emissions; (ii) adapting and building forest resilience to climate change; and (iii) sustainably increasing forest productivity and incomes. These three CSF objectives can be achieved by tailoring policy measures and actions to regional circumstances in Member States forest sectors.

Case description

The current annual mitigation effect of EU forests via contributions to the forest sink, material substitution and energy substitution is estimated at 569 $MtCO_2$ yr^{-1}, or 13% of total current EU emissions. With the right set of incentives in place at EU and Member States levels, it was found that the EU has the potential to achieve an additional combined mitigation impact through the implementation of CSF goals, of 441 $MtCO_2$ yr^{-1} by 2050. Also, with the Green Deal more emphasis will be placed on forests, forest management and the provision of renewables. It is the diversity of measures (from strict reserves to more intensively managed systems while adapting the resource) that will determine the success. Only with co-benefits in e.g. nature conservation, soil protection, and provision of renewables, wood for buildings and income, the mitigation and adaptation measures will be successful.

Interactions and limitations

Climate Smart Forestry is now taking shape across Europe with various research and implementation projects. The larger (often) public owners will have to be in the forefront. They will have to establish examples and take care of outreach to 16 million small owners. However, the right triggers and incentives are often still lacking. E.g. adapting the spruce forest areas in Central Europe to climate change requires knowledge about different species and different management options and eventually use in industry. It requires alternative species to be available from the nurseries. Further, better monitoring will be needed.

Lessons

Finalising: a joint effort between the European Commission, Member States, industry, research and large public owners will be needed to tackle the challenges as outlined above. Only then Climate smart forestry will make its way into a large roll out and into practice.

7.4.2.4 Fire management (forest and grassland/savanna fires)

Activities, co-benefits, risks and implementation opportunities and barriers. Fire management is aimed at safeguarding life, property, and resources through the prevention, detection, control, restriction, and suppression of fire in forests and other ecosystems, including grasslands and savannas (SRCCL Chapter 6). It includes the improved use of fire for sustainable ecosystem management of forested and savanna ecosystems, including wildfire prevention and prescribed burning. Prescribed burning is used to reduce the risk of large, uncontrollable fires in forest areas. Controlled burning is an effective economic method of reducing fire danger and stimulating natural reforestation under the forest canopy and after clear felling. Co-benefits of fire management include reduced air pollution and improved population health, prevention of soil erosion and land degradation and is used in rangelands to conserve biodiversity and to enhance forage quality.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL, fire management is included as one of the nine options that can deliver medium-to-large benefits across multiple land challenges (climate change mitigation, adaptation, desertification, land degradation, and food security) (*high confidence*). Total emissions from fires have been on the order of 8.1 $GtCO_2$-eq yr^{-1} for the period 1997–2016 (SRCCL, Chapter 2 and Cross-Chapter Box 3). Reduction in fire CO_2 emissions due to fire suppression and landscape fragmentation associated with increases in population density is calculated to enhance land carbon uptake by 0.48 $GtCO_2$-eq yr^{-1} for the 1960–2009 period (Arora and Melton 2018) (SRCCL, Table 6.16).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL).
Savannas. Savannas constitute the most fire-prone vegetation type on Earth and are a significant source of greenhouse gas emissions. Savanna fires contributed 62% (4.92 $PgCO_2$-eq yr^{-1}) of gross global mean fire emissions between 1997 and 2016. Although regrowth from vegetation postfire tends to sequester the carbon dioxide (CO_2) released into the atmosphere, methane (CH_4), and nitrous oxide (N_2O) emissions persist in the atmosphere and contributed an approximate net of 2.1 PgCO2-eq yr^{-1} (Lipsett-

Moore et al. (2018). Implementation of prescribed burning with low intensity fires, principally in the early dry season, to effectively manage the risk of wildfires occurring in the late dry season are associated with reduction in (Whitehead et al. 2014). Considering this fire management practice, estimates of global opportunities for emissions reductions of 69.1 $MtCO_2$-eq yr^{-1} in Africa (29 countries, with 20 least developed African countries accounting for 74% of the mitigation potential), 13.3 $MtCO_2$-eq yr^{-1} in South America (six countries), and 6.9 $MtCO_2$-eq yr^{-1} in Australia and Papua New Guinea (Lipsett-Moore et al. (2018). In Australia, savanna burning emissions abatement methodologies have been available since 2012, and there are currently 72 registered projects covering approximately 32 Mha. Abatement to date has exceeded 4 $MtCO_2$-eq principally through the application of low intensity early dry season fire management to reduce the amount of biomass combusted in higher intensity late dry season (LDS) fires (Lynch et al. 2018).

Forests. Fire is also a prevalent forest disturbance. About 98 Mha of forest were affected by fire in 2015, mainly in the tropical domain, where fire affected about 4 % of the total forest area in that year (FAO 2020). More than two-thirds of the forest burned area was in Africa and South America. Prescribed fires are also applied routinely in forests worldwide for fuel reduction and ecological reasons (Kalies and Kent, 2016). The Australian Government has sanctioned greenhouse gas emissions (GHG) abatement methodologies to meet international emissions reduction obligations. Australia prescribed fire has been implemented in Eucalyptus forests since the mid-1950s to reduce fuels and wildfire risk (McCaw, 2013). In southern forest landscapes, fire resilience is increasingly managed, particularly in the southwestern United States, which has experienced drought and widespread, high-severity wildfires. In these forests, fire exclusion management, coupled with a warming climate, has led to increasingly massive and severe wildfires (Hurteau et al. 2014). However, the impacts of prescribed fires in forests in reducing carbon emissions is still inconclusive. An extensive literature review of relevant empirical and modelling studies assessing prescribed fire and wildfire regimes and their effects (Hunter and Robles, 2020) suggest that the results of prescribed fire on wildfire and total emissions are highly dependent on wildfire activity, as it influences the rate at which wildfires overlap areas treated with prescribed fire. Studies that assume prescribed fire essentially replaces wildfire (i.e., the same total area burned), increases in prescribed fire activity can lead to reductions in total fire emissions. Still, effects were significant only in areas with high rates of wildfire. Other studies indicate some positive impacts of prescribed fires in association with other fuel reduction techniques. Fuel treatments can reduce drought-mortality if tree density is uncharacteristically high and increase long-term carbon storage by reducing high-severity fire probability (Loudermilk et al. 2017, Flanagan et al. 2019, Stephens et al. 2019). Prescribed burning in thinning operations may be critical to maintaining C stocks and reducing C emissions in the future where extreme fire weather events are more frequent (Krofcheck et al. 2016, Hurteau et al. 2019). However, it is uncertain how ongoing climate change will influence the probability of wildfire and the carbon stores and uptake in these systems (Hurteau et al. 2019, Bowman et al. 2020, Goodwin et al. 2020).

Challenges for savanna fire management aiming at emissions abatement include, but are not limited to, legal and policy issues, equity and rights concerns, governance, capacity, and research needs (Russell-Smith et al. 2017). The need to develop national fire management policies that address the fire problems at the landscape level, including cross-sectoral/interagency approaches in fire management, is underscored as well as the involvement of local communities in active fire prevention, the sound and safe use of fire in land management (Goldammer 2016). The feasibility of large-scale prescribed burning in forests is also challenging, making the implementation more practical in lands managed by the central governments (Wiedinmyer and Hurteau 2010). Studies on the potential impacts of climate change on forest fire activity point out that the fire environment will become more conducive to fire. Land management approaches will need to consider the new conditions (e.g., the proportion of days in fire seasons with the potential for unmanageable fires will increase across Canada's forest, more than doubling in some regions in northern and eastern boreal forest) (Wotton et al. 2017).

Critical assessment and conclusion. Savanna fires produce significant emissions globally but the management through prescribed fires in early dry season could mitigate emissions in different regions, particularly in Africa. Evidence is less clear for fire management of forests, with the contribution to mitigate GHG depending on many factors that affect the carbon balance. Although prescribed burning is a widely promoted to reduce uncontrolled wildfires in forests, the benefits for the management of carbon stores are controversial especially in the in the face of climate change-driven fires (Wotton et al. 2017; Bowman et al. 2020)

7.4.2.5 Reduce conversion of grasslands and savannas

Activities, co-benefits, risks and implementation opportunities and barriers. Grasslands are defined as terrestrial ecosystems dominated by herbaceous and shrub vegetation and maintained by fire, grazing, drought, or freezing temperatures (White et al. 2000). According to the modified IGBP land cover map, approximately 40.5 % of the terrestrial area (excluding Greenland and Antarctica) is grassland (i.e., 52.5 million km^2) divided as 13.8% woody savanna and savanna; 12.7% open and closed shrub; 8.3 % non-woody grassland; and 5.7% is tundra (White et al. 2000). Every region of the world contains grasslands. Sub-Saharan Africa and Asia have the most extensive total area, 14.5 and 8.9 million km^2, respectively, while Australia, the Russian Federation, China, the United States, and Canada concentrate the largest grassland area. Grasslands store 50% more carbon than forests worldwide and represent around 20% of global soil organic carbon (Conant 2010). Reducing the conversion of grasslands and savannas to croplands prevents soil carbon losses by oxidation, and to a smaller extent, biomass carbon loss due to vegetation clearing (SRCCL, Chapter 6). Restoration of grasslands through enhanced soil carbon sequestration, including a) management of vegetation, b) animal management, and c) fire management, was also included in the SRCCL and is covered in Section 7.4.3.1. Similar to other measures that reduce conversion, conserving carbon stocks in grasslands and savannas can be achieved by controlling conversion drivers (e.g., commercial and subsistence agriculture, see Section 7.3) and improving policies and management. In addition to mitigation, conserving grasslands provide various socio-economic and environmental benefits. Pasture represents primary feed resources for livestock worldwide, and sown pastures and rangelands contribute to the livelihoods of more than 800 million people (Reynolds et al. 2005). Additional benefits of grassland conservation include biodiversity and habitat conservation and improved soil water holding capacity (Ryals et al. 2015, Bengtsson et al. 2019). A key barrier to implementation is cost. Poverty and economic marginalisation often characterise the human populations managing grasslands. Changes in management practice are associated with initial investment costs, annual operating costs, and opportunity costs of income foregone by undertaking the activities needed for avoiding conversion of grasslands (Lipper et al. 2010; 2011).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL reported a mitigation potential for reduced conversion of grasslands and savannas of 0.03–0.12 $GtCO_2$-eq yr^{-1} (SRCCL: Griscom et al. 2017) considering the higher loss of soil organic carbon in croplands (Sanderman et al. 2017). Assuming an average starting soil organic carbon stock of grasslands (Poeplau et al. 2011), and the mean annual global cropland conversion rates (1961–2003) (Krause et al. 2017), the equivalent loss of soil organic carbon over 20 years would be 14 $GtCO_2$-eq, i.e. 0.7 $GtCO_2$ yr^{-1} (SRCCL, Chapter 6). IPCC AR5 and AR4 did not explicitly consider the mitigation potential of avoided conversion of grasslands-savannas but the management of grazing land is accounted for considering plant, animal, and fire management with a mean mitigation potential of 0.11-0.80 tCO_2-eq ha^{-1} yr^{-1} depending on the climate region. This resulted in 0.25 $GtCO_2$-eq yr^{-1} at USD 20/tCO_2 to 1.25 $GtCO_2$-eq yr^{-1} at USD 100/tCO_2 by 2030.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Unlike most of the measures covered in Section 7.4, there are currently no global, spatially explicit mitigation potential estimates for reduced grassland conversion to generate technical and economic potentials by region. Literature developments since AR5 and SRCCL are studies that provide mitigation estimates in one or a few countries or regions. Modelling experiments comparing Californian forests and grasslands found that grasslands resulted in a more resilient C sink than forests to future climate change (Dass et al. 2018). In North America, grassland conversion was the source for 77% of all new croplands from 2008-2012 (Lark et al. 2015). Avoided conversion of North American grasslands to croplands presents an economic mitigation potential of 0.024 $GtCO_2$-eq yr^{-1} and technical potential of 0.107 $GtCO_2$-eq yr^{-1} (Fargione et al. 2018). This potential is related mainly to root biomass and soils (81% of emissions from soils). Estimates of GHG emissions from any future deforestation in Australian savannas also point to the potential mitigation of around 0.024 $GtCO_2$-eq yr^{-1} (Bristow et al. 2016). The expansion of the Soy Moratorium (SoyM) from the Brazilian Amazon to the Cerrado (Brazilian savannas) would prevent the direct conversion of 3.6 Mha of native vegetation to soybeans by 2050 and avoid the emission of 0.02 $GtCO_2$-eq yr^{-1} (Soterroni et al. 2019).

Critical assessment and conclusion. Reduce conversion of grasslands and savannas showed considerable mitigation potential with most of the carbon sequestration in belowground biomass and soil organic matter. However, estimates of potential are still based on few studies and vary according the levels of soil carbon, and ecosystem productivity (e.g. in response to rainfall distribution). Conservation of grasslands presents significant benefits for desertification control, especially in in arid areas (SRCCL, Chapter 3). Carbon offsets from avoided conversion can help protect at-risk grasslands, reduce GHG emissions, and produce positive outcomes for biodiversity and landowners (Ahlering et al. 2016). Tropical rainforest regions have been the primary target for REDD because of the high carbon stocks and rapid deforestation in recent decades. Conversion grasslands and savannas has received less national and international attention, despite growing evidence of concentrated cropland expansion into these areas.

7.4.2.6 Reduce conversion of peatlands

Activities, co-benefits, risks and implementation barriers. Peatlands are carbon-rich wetland ecosystems with organic soil horizons in which soil carbon concentrations may be as high as 60% (Kauffman et al. 2017). Reducing the conversion of peatlands avoids emissions of above- and below-ground biomass and soil carbon due to vegetation clearing, fires, and peat decomposition from drainage. Similar to deforestation, conserving carbon stocks in peatlands can be achieved by controlling the drivers of conversion (e.g. commercial and subsistence agriculture, mining, urban expansion) and improving governance and management. Avoiding emissions through peatland conservation is urgent because peatland carbon stocks accumulate slowly and persist over millennia; loss of existing stocks cannot be easily reversed over the decadal timescales needed to meet the Paris Agreement (Goldstein et al. 2020). The main co-benefits of reducing conversion of peatlands include conservation of a unique biodiversity including many critically endangered species, provision of water quality and regulation, and improved public health through decreased fire-caused pollutants (Smith et al. 2019, Griscom et al. 2017). The major negative side effect of reducing peatland conversion is increasing competition for other land uses, including agriculture and alternative land-based mitigation measures such as afforestation and bioenergy crops.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL (Chapters 2 and 6), it was estimated that avoided peat impacts could deliver 0.45–1.22 $GtCO_2$-eq yr^{-1} technical potential by 2050 (*medium confidence*) (Griscom et al. 2017; Hawken 2017; Hooijer et al. 2010). The mitigation potential estimates cover tropical peatlands and include CO_2, N_2O and CH_4 emissions. The mitigation potential is derived from quantification of losses of carbon stocks due to land conversion, shifts in greenhouse gas fluxes, alterations in net ecosystem productivity, input factors such as fertilisation needs, and biophysical climate impacts (e.g., shifts in albedo, water cycles, etc). Tropical peatlands account for only ~10% of peatland area and ~20% of peatland carbon stock but ~80% of peatland carbon emissions, primarily from peatland conversion in Indonesia (~60%) and Malaysia (~10%) (Hooijer et al. 2010; Page et al.

2011, Leifeld & Menichetti 2018). While the total mitigation potential of peatland conservation is considered moderate, the per hectare mitigation potential is the highest among land-based mitigation measures (Roe et al. 2019).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies continue to report high carbon stocks in peatlands and emphasise the vulnerability of peatland carbon after conversion. The carbon stocks of tropical peatlands are among the highest of any forest, 330-1,160 MtC ha^{-1} in the Peruvian Amazon (Bhomia et al. 2019) and 558-5,591 Mt C ha-1 in Indonesia (Basuki et al. 2016, Kauffman et al. 2017). Ninety percent of tropical peatland carbon stocks are vulnerable to emission during conversion and may not be recoverable through restoration; in contrast, boreal and temperate peatlands hold similar carbon stocks (392-1,531 MgC ha^{-1}) but only 30% of northern carbon stocks are vulnerable to emission during conversion and irrecoverable through restoration (Goldstein et al. 2020). Based on the most recent studies, the technical global mitigation potential is 0.51-2.02 $GtCO_2$-eq yr^{-1} (Table 7.5), of which approximately 72% is achieved through avoided soil carbon impacts, with the remainder through avoided impacts to vegetation (Bossio et al. 2020). Economic analysis indicates that 60% of peatland mitigation can be achieved at a low cost (<10 USD $MgCO_2$-eq yr^{-1}) (Griscom et al. 2017). Recent model projections show that both peatland protection and peatland restoration (Section 7.4.2.7) are needed to achieve a 2ºC mitigation pathway and that peatland protection and restoration policies will have minimal impacts on regional food security (Leifeld et al. 2019, Humpenöder et al. 2020).

Regionally, 80% of technical mitigation potential (~661 $MtCO_2$-eq yr^{-1}) and 80% of economic potential at USD100/tCO_2 (~595 $MtCO_2e$ yr^{-1}) are in Southeast Asia (Table 7.5). The remaining 20% mitigation potential is shared among the remaining regions, ranging from 6-56 $MtCO_2$-eq yr^{-1}. However, these estimates do not account for the extensive peatlands recently reported in the Congo Basin, estimated to cover 145,500 km2 and contain 30.6 Pg C, as much as 29% of total tropical peat carbon stock (Dargie et al. 2017). These Congo peatlands are relatively intact; continued preservation is needed to prevent major emissions (Dargie et al. 2019). In northern peatlands that are underlain by permafrost (roughly 50% of the total peatlands north of 23º latitude, (Hugelius et al. 2020), climate change (i.e. warming) is the major driver of peatland conversion (e.g. through permafrost thaw) (Schuur et al. 2015, Goldstein et al. 2020). However, in non-permafrost boreal and temperate peatlands, reduction of peatland conversion is also a cost-effective mitigation strategy.

Peatlands are sensitive to climate change and there is *low confidence* about the future peatland sink globally (SRCCL, Chapter 2). Some peatlands have been found to be resilient to climate change (Minayeva and Sirin 2012), but the combination of conversion and climate change may make them vulnerable to fire (Sirin et al. 2011). Carbon sequestration is generally projected to increase in northern peatlands, where warming will increase plant productivity relative to microbial decomposition (Gallego-Sala et al. 2018, Chaudhary et al. 2020). However, permafrost thaw may shift northern peatlands from a net carbon sink to net source (Hugelius et al. 2020). Uncertainties in peatland extent and the magnitude of existing carbon stocks, in both northern (Loisel et al. 2014) and tropical (Dargie et al. 2017) latitudes limit understanding of current and future peatland carbon dynamics (Minasny et al. 2019).

Critical assessment and conclusion. Based on studies to date, there is *high confidence* that peatland conservation has a technical potential of 0.51-2.02 $GtCO_2$-eq yr^{-1} (median 0.69) of which 0.68 $GtCO_2$-eq yr^{-1} is available at USD 100/tCO_2. High per hectare mitigation potential, low cost of implementation, and high rate of co-benefits indicate that conservation of peatlands, particularly in tropical countries, support the effectiveness of this mitigation strategy (Roe et al. 2019). Feasibility of reducing peatland conversion may depend on countries' governance and financial capacity (Griscom et al. 2020).

7.4.2.7 Peatland restoration

Activities, co-benefits, risks and implementation barriers. Peatland restoration involves restoring degraded and damaged peatlands, for example through rewetting and revegetation, which both increases carbon accumulation in vegetation and soils and avoids ongoing CO_2 emissions. Peatlands only account for ~3% of the terrestrial surface, predominantly occurring in boreal ecosystems (78%), with a smaller proportion in tropical regions (13%), but may store ~600 Gt of C or 21% of the global total soil organic C stock of ~3000 Gt (Leifeld and Menichetti 2018, Page et al. 2011). Peatland restoration delivers co-benefits for biodiversity, as well as regulating water flow and preventing downstream flooding, while still allowing for extensive management such as paludiculture (Tan et al. 2021). Rewetting of peatlands also reduces the risk of fire, further protecting peat carbon stocks and improving public health by reducing fire-caused pollutants (Smith et al. 2019). A potential risk is that since large areas of tropical peatlands and some northern peatlands have been drained and cleared for agriculture, their restoration could displace food production and damage local food supply, though the global impact would be limited due to the relatively small areas affected. Collaborative and transparent planning processes are needed to reduce conflict between competing land uses (Tanneberger et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Large areas (0.51Mkm2) of global peatlands are degraded of which 0.2 are tropical peatlands (Griscom et al. 2017, Leifeld and Menichetti 2018). According the SRCCL, peatland restoration could deliver technical mitigation potentials of 0.15 - 0.81GtCO_2-eq yr^{-1} by 2030 (*low confidence*) (Chapter 2 and 6 of the SRCCL; (Couwenberg et al. 2010; Griscom et al. 2017), though there could be an increase in methane emissions after restoration (Jauhiainen et al. 2008) The mitigation potential estimates cover global peatlands and include CO_2, N_2O and CH_4 emissions. Peatlands are highly sensitive to climate change (*high confidence*), however there are currently no studies that estimate future climate effects on mitigation potential from peatland restoration.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). The most recent literature and reviews indicate with a high level of confidence that restoration would decrease CO_2 emissions and with *medium confidence* that restoration would decrease net GHG emissions from degraded peatlands (Wilson et al. 2016, Ojanen & Minkkinen 2020, van Diggelen et al. 2020). Although rewetting of drained peatlands increases CH4 emissions, this effect is outweighed by decreases in CO_2 and N_2O emissions (Günther et al. 2020). Restoration and rewetting of almost all drained peatlands is needed by 2050 to meet 1.5-2ºC pathways (Leifeld et al. 2019); immediate rewetting and restoration minimises the warming from cumulative CO_2 emissions (Nugent et al. 2019). Restoring peatlands costs 3.4 times less nitrogen and involves a much smaller land area demand than mineral soil carbon sequestration (Leifeld & Menichetti 2018).

According to recent data, the technical mitigation potential for global peatland restoration is estimated at 0.5-1 GtCO_2-eq yr^{-1} (Leifeld & Menichetti 2018, Griscom et al. 2020, Bossio et al. 2020, Table 7.5), with 80% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). Current mitigation pathways do not account for emissions from degraded peatlands or for emission reductions following restoration, but a recent study indicates that peatland restoration will be key to achieving a net carbon sink in the land system by 2100 (Humpenöder et al. 2020). The regional mitigation potentials of all peatlands outlined in Table 7.5 reflect the country-level estimates from Griscom et al. 2017 (global potentials reported in SRCCL). The economic mitigation potential at USD 100/tCO_2 is 232 MtCO_2-eq yr^{-1} (60% of global potential) in Asia and developing Pacific, 22 MtCO_2-eq yr^{-1} in Africa, 71 MtCO_2-eq yr^{-1} in Developed countries (about 60 in Europe and 10 in North America), 55 MtCO_2-eq yr^{-1} in Eastern Europe and West-Central Asia, and 11 MtCO_2-eq yr^{-1} in Latin America and Caribbean (Table 7.5).

Climate mitigation effects of peatland rewetting depend on the climate zone and land use. Recent analysis shows the strongest mitigation effect from rewetting drained tropical peatlands and drained temperate and boreal peatlands used for agriculture (Ojanen & Minkkinen 2020). However, estimates of emission factors from rewetting drained tropical peatlands remain uncertain (Wilson et al. 2016, Murdiyarso et al. 2019). Topsoil removal, in combination with rewetting, may improve restoration success and limit CH4 emissions during restoration of highly degraded temperate peatlands (Zak et al. 2018). In temperate and boreal regions, co-benefits mentioned above are major motivations for peatland restoration (Chimner et al. 2017, Tanneberger et al. 2020).

Critical assessment and conclusion. Based on studies to date, there is moderate to *high confidence* that peatland restoration has a technical potential of 0.49-1.0 $GtCO_2$-eq yr^{-1} (median 0.71) of which 0.39 $GtCO_2$-eq yr^{-1} is available at USD 100/tCO_2. The large land area of degraded peatlands suggests that significant emissions reductions could occur through large-scale restoration especially in tropical peatlands. There is a high certainty in the large carbon stocks of peat forests (1770 - 4022 Mg C ha^{-1}) and large rates of carbon loss associated with land cover change (1487 – 3262 Mg C ha^{-1}). However, large-scale implementation of tropical peatland restoration may be limited by financial costs.

7.4.2.8 Reduce conversion of coastal wetlands

Activities, co-benefits, risks and implementation barriers. Reducing conversion of coastal wetlands, including mangroves, marshes and seagrass ecosystems, avoids emissions from above and below ground biomass and soil carbon through avoided degradation and/or loss. Coastal wetlands occur mainly in estuaries and deltas, which is where 20% of the human population of the planet live at densities that are three-fold that in inland areas (Small & Nicholls 2003). The carbon stocks of these ecosystems are referred to as "blue carbon" and include the carbon stored in within the soil, the living biomass aboveground (e.g., leaves, branches, stems), the living biomass belowground (e.g., roots and rhizomes), and the non-living biomass (litter and dead wood). Avoiding emissions through coastal wetland conservation is urgent because these carbon stocks accumulate slowly and persist over millennia; loss of existing stocks cannot be easily reversed over the decadal timescales needed to meet the Paris Agreement (Goldstein et al. 2020). The main drivers of conversion, loss and degradation of coastal wetlands include aquaculture, agriculture, salt ponds, urbanisation and infrastructure development, the extensive use of fertilisers, and extraction of water resources (Lovelock et al. 2018). Reduced conversion as a mitigation measure has many co-benefits, including biodiversity conservation, fisheries production (food security), soil stabilisation, water flow and water quality regulation, flooding and storm surge prevention, and increased resilience to cyclones (Windham-Myers et al. 2018). Risks associated with the mitigation potential of coastal wetland conservation include uncertain permanence under future climate scenarios, including the effects of coastal squeeze, where coastal wetland area may be lost if upland area is not available for migration as sea levels rise (Lovelock & Reef 2020). Preservation of coastal wetlands also conflicts with other land use in the coastal zone, including aquaculture, agriculture, and human development; economic incentives are needed to prioritise wetland preservation over more profitable land use. Integration of policies and efforts aimed at coastal climate mitigation, adaptation, biodiversity conservation, and fisheries, for example through Integrated Coastal Zone Management and Marine Spatial Planning, will bundle climate mitigation with co-benefits and optimise outcomes (Herr et al. 2017).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Coastal wetlands contain high, yet variable, organic carbon stocks, leading to a range of estimates of the global mitigation potential of reduced conversion. The SRCCL (Chapter 2) and SROCCC (Chapter 5), report a technical mitigation potential of 0.15-5.35 $GtCO_2$-eq yr^{-1} by 2050 (Pendleton et al. 2012, Lovelock et al. 2017, Howard et al. 2017, Griscom et al. 2017) The mitigation potential is derived from quantification of losses of carbon stocks in vegetation and soil due to land conversion, shifts in greenhouse gas fluxes associated with land use, and alterations in net ecosystem productivity. Loss rates of coastal wetlands have been estimated at 0.2-3% yr-1, depending on the vegetation type and location (Howard et al. 2017, Atwood et al. 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies have improved quantification of carbon stocks and emissions from conversion of coastal wetlands. Some advances have been made in mapping coastal wetland extent and rates of loss but this remains a source of uncertainty.

Mangroves. Based upon recent studies, the mean ecosystem carbon stock of mangroves is 3131 $MtCO_2$-eq ha^{-1}, (Kauffman et al. 2020), among the largest carbon stocks on Earth. In contrast, the IPCC Tier 1 default TECS value (IPCC 2014) for mangroves is 1878 $MtCO_2$-eq ha^{-1}, which is only 60% of the calculated global mean. There is variability in the carbon stocks of the mangroves of the world with the mean ecosystem stock ranging from 796 $MtCO_2$-eq ha^{-1} in the hyper arid-hypersaline mangroves of the middle east to 4209 $MtCO_2$-eq ha^{-1} in the equatorial islands of Oceania (Schile et al. 2017, Kauffman et al. 2020). Mangroves globally store about 42.9 $GtCO_2$-eq; an aboveground carbon stock of 5.9 $GtCO_2$-eq and a belowground carbon stock of 37.4 $GtCO_2$-eq. The largest carbon stocks are found in Asia (16.5 $GtCO_2$-eq), Africa (8.1 $GtCO_2$-eq), North America (7.0 $GtCO_2$-eq) and Oceania (7.0 $GtCO_2$-eq) (Kauffman et al. 2020). Most of the ongoing loss in coastal wetlands is occurring in the tropics (Friess et al. 2019). Globally, 1.67% of all mangroves were deforested between 2000 and 2015 (i.e. a loss of 278,049 ha), releasing 0.55 Pg CO_2-eq in this time frame (Sanderman et al. 2018). Annually, 0.26%–0.66% of the world's mangrove forests were lost between 2000 and 2012 (Hamilton & Casey 2016), suggesting avoiding mangrove conversion has the technical potential to mitigate approximately 0.070 to 0.18 Pg CO_2-eq yr^{-1} globally, or 1,938 $MtCO_2$-eq ha^{-1} on a per area basis (Kauffman et al. 2017).

Marshes. Tidal marshes are the dominant blue carbon ecosystem over much of the temperate zone and polar coastal regions of the world but also occur in the high intertidal zone in the tropics. While dominated by herbaceous species, coastal are also significant global carbon stocks. For example, the mean total ecosystem carbon stock of North American marshes including the entire soil profile is 493 Mg C ha^{-1} of which only 48-53% is found in the top 1 m of soils. The top 1 m of tidal wetland soils and estuarine sediments of North America contains 1.9 ± 1.0 Pg C) (Windham-Myers et al. 2018). Yet this is a great underestimate because much of the carbon stored in these ecosystems is below 1m in depth and when disturbed is vulnerable to loss. Including the entire soil profile (as deep as 3 m) resulted in estimates of 1.94 Pg of carbon stored in North American mangroves and 0. 95 Pg C stored in North American marshes. Vast areas of coastal wetlands in temperate zones have already been lost. For example, about 85% of vegetated tidal wetlands from estuaries on the west coast, USA have been lost (Brophy et al. 2019). Similar losses have been reported for European tidal wetlands (Lovelock et al. 2018). The greatest mitigation benefits in these temperate regions would be in restoration.

Seagrasses. Seagrass meadows occur in shallow coastal waters of every continent except Antarctica; seagrass blue carbon stocks are highly variable across estuaries and between species (Bedulli et al. 2020, Ricart et al. 2020). Recent efforts to map global seagrass extent identified 160,387 km2 of seagrass in 103 countries with moderate to *high confidence* and an additional 106,175 km2 of seagrass extent in another 33 countries with *low confidence*; 17% of countries with confirmed seagrass presence lacked spatial data, highlighting the lack of basic data (e.g. presence/absence) needed to inform seagrass conservation efforts (McKenzie et al. 2020). In Europe, seagrass area decline peaked in the 1970s at -33% $decade^{-1}$ and has increased during the 2000s at 20% $decade^{-1}$, a trend that may be explained by management actions to improve water quality (de los Santos et al. 2019). Protection of seagrass meadows is an emerging priority for marine conservation, motivated by co-benefits of numerous ecosystem services as well as climate mitigation potential (UNEP 2020). However, seagrasses are sensitive to impacts from warming temperatures and marine heat waves (Smale et al. 2019); blue carbon stored in seagrass meadow sediments can be emitted after disturbance from temperature stress (Arias-Ortiz et al. 2018, Salinas et al. 2020), potentially limiting the permanence of climate mitigation.

According to recent data, the technical mitigation potential for conservation of coastal wetlands is 0.06-2.25 $GtCO_2$-eq yr^{-1} (Howard et al. 2017, Griscom et al. 2020, Bossio et al. 2020) with 80% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). Regional potentials (Table 7.5) based on country-level estimates from Griscom et al. (2020) show the potential of mangrove protection in tropical countries; seagrass protection was not included due to lack of country-level data on seagrass distribution and conversion. Regional estimates show that similar to peatlands, about 80% of mitigation potential for avoided mangrove conversion is in Southeast Asia and Developing Pacific (106 $MtCO_2$-ep yr^{-1} technical potential, 32 $MtCO_2$-eq yr^{-1} economic potential at USD100/tCO_2). Latin America and Caribbean have 14 and 4 $MtCO_2$-eq yr^{-1} technical and economic potential, respectively. Developed countries have 5 and 1 $MtCO_2$-eq yr^{-1} respectively, and Africa and the Middle East have 2 and 1 $MtCO_2$-eq yr^{-1} respectively.

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that coastal wetland protection has a technical potential of 0.06-2.25 $GtCO_2$-eq yr^{-1} (median 0.23) of which 0.06-0.27 $GtCO_2$-eq yr^{-1} is available at USD100/tCO_2. There is a high certainty (robust evidence, high agreement) that coastal ecosystems have among the largest carbon stocks of any ecosystem. Further, it is with high certainty (robust evidence, high agreement) that greenhouse gas emissions from land conversion of coastal ecosystems greatly exceed that of upland ecosystems. As such, it is with high certainty that while limited in area, the high carbon stocks, large greenhouse gas emissions arising from their conversion, and the other important ecosystem services they provide suggest conservation of intact blue carbon ecosystems can be a very effective mitigation strategy in coastal environments.

7.4.2.9 Coastal wetland restoration

Activities, co-benefits, risks and implementation barriers. Coastal wetland restoration involves restoring degraded or damaged coastal wetlands including mangroves, salt marshes, and seagrass ecosystems, leading to sequestration of 'blue carbon' in wetland vegetation and soil (SRCCL Ch 6, SROCCC Ch 5). Successful approaches to wetland restoration include: (1) passive restoration, the removal of anthropogenic activities that are causing degradation or preventing recovery; and (2) active restoration, purposeful manipulations to the environment in order to achieve recovery to a naturally functioning system (Elliott et al. 2016). In addition to the creation or expansion of new habitat area, restoration can involve management strategies to optimise carbon sequestration, e.g. by reducing nutrient pollution (Macreadie et al. 2017). Restoration of coastal wetlands delivers many other co-benefits, including enhanced water quality, biodiversity, aesthetic values, fisheries production (food security), and protection from rising sea levels and storm impacts (Barbier et al. 2011, Hochard et al. 2019, Sun & Carson 2020, Duarte et al. 2020). Since large areas of coastal wetlands are degraded, successful restoration could also potentially deliver moderate benefits for addressing land degradation, with 0.29 Mkm^2 of all coastal wetlands globally (0.11 Mkm^2 of mangroves) considered feasible for restoration (Griscom et al. 2017). Risks associated with the mitigation potential of coastal wetland restoration include uncertain permanence under future climate scenarios, partial offsets of mitigation through enhanced methane and nitrous oxide release and carbonate formation, and competition with other land uses, including aquaculture and human settlement and development in the coastal zone (SROCCC, Ch. 5). To date, many coastal wetland restoration efforts worldwide do not succeed due to failure to address the drivers of wetland degradation (van Katwijk et al. 2016), incomplete understanding of the interactions between wetland vegetation and the biophysical environment (Li et al. 2018), and poor site selection, e.g. planting mangroves in intertidal mud-flats below mean sea level where they cannot persist (Kodikara et al. 2017). Variable costs of restoration efforts, depending on the ecosystem type, restoration method, and location of restoration, can also constrain large-scale efforts (Taillardat et al. 2020). Restoration projects that involve local communities at all stages and consider both biophysical and socio-political context are more likely to succeed (Brown et al. 2014; Wylie et al. 2016).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL reported that mangrove restoration has the technical potential to mitigate the release of 0.07 $GtCO_2$ yr^{-1} through rewetting (Crooks et al. 2011) and take up 0.02–0.84 $GtCO_2$ yr^{-1} from vegetation biomass and soil enhancement through 2030 (*medium confidence*) (Griscom et al. 2017). The SROCCC concluded that cost-effective coastal blue carbon restoration had a potential of ~0.15-0.18 $GtCO_2$-eq yr^{-1} (0.04-0.05 GtC yr^{-1}), a low global potential compared to other ocean-based solutions but with extensive co-benefits and limited adverse side effects (Gattuso et al. 2018). Quantification of the mitigation potential is limited due to high site-specific variation in carbon sequestration rates and uncertainties regarding the response of coastal wetlands to future climate change (Jennerjahn et al. 2017, Nowicki et al. 2017), dynamic changes in distributions (Kelleway et al. 2017, Wilson & Lotze 2019) and other factors affecting long-term sequestration and climatic benefits, such as methane release (Al-Haj & Fulweiler 2020) and carbonate formation (Saderne et al. 2019).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies generally affirm previous estimates and emphasise the timeframe (decadal to century) needed to achieve the full mitigation potential of coastal wetland restoration (Duarte et al. 2020, Taillardat et al. 2020). A recent case study provided the first project-derived estimate of the net greenhouse gas benefit from seagrass restoration at 1.54 tCO_2-eq (0.42 MgC) ha^{-1} yr^{-1}, comparable to the default emission factor provided in the Wetlands Supplement (IPCC 2014); this climate benefit was achieved 10 y after restoration began (Oreska et al. 2020). Recent studies of rehabilitated mangroves also indicate that annual carbon sequestration rates in biomass and soils can return to natural levels within decades of restoration (Cameron et al. 2019, Sidik et al. 2019). Meta-analysis shows increasing carbon sequestration rates over the first 15 y of mangrove restoration with rates stabilising at 25.7±7.7 tCO_2-eq (7.0±2.1 MgC) ha^{-1} yr^{-1} through forty years, although restoration success depends on location, climate, sediment type, and restoration methods (Sasmito et al. 2019). These rates are substantially lower than potential emissions from mangrove conversion, which recent estimates place at 120 tCO_2-eq ha^{-1} yr^{-1} for conversion to shrimp ponds (Arifanti et al. 2019), greatly exceeding the IPCC emission factor for coastal wetland soil after drainage (28 tCO_2-eq ha^{-1} yr^{-1}, IPCC 2014) and indicating the long timeframe needed to recover lost carbon stocks via restoration. Overall, 30% of mangrove soil carbon stocks and 50-70% of marsh and seagrass carbon stocks are unlikely to recover within 30 years of restoration, underscoring the importance of preventing conversion of coastal wetlands (Sec. 7.4.2.8) (Goldstein et al. 2020).

According to recent data, the technical mitigation potential for global coastal wetland restoration is 0.04-0.84 $GtCO_2$-eq yr^{-1} (Griscom et al. 2020, Bossio et al. 2020, Table 7.5) with 60% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). Regional potentials based on country-level estimates from Griscom et al. (2020) show the potential of mangrove restoration in tropical countries; seagrass restoration was not included due to lack of country-level data on seagrass distribution and conversion (but see McKenzie et al. (2020) for updates on global seagrass distribution). Regional mitigation potential of mangrove restoration is fairly small: 8 $MtCO_2$-eq yr^{-1} technical potential and 2 $MtCO_2$-eq yr^{-1} economic potential at USD 100/tCO_2 in Southeast Asia and Developing Pacific, 7 and 1 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean, and 2 and 1 $MtCO_2$-eq yr^{-1} in Africa and the Middle East respectively (Table 7.5). However, the mitigation can be quite significant for countries with extensive coastlines, exceptionally large areas of mangrove (e.g., Indonesia, Brazil) and for small island states where mangroves have been shown to comprise 24-34% of their total national carbon stock (Donato et al. 2012). Mangrove restoration is generally more cost-effective than seagrass or salt marsh restoration (Taillardat et al. 2020), although coastal restoration success does not yet scale with cost (Bayraktarov et al. 2016). Major successes in both active and passive restoration of seagrasses have been documented in North America and Europe (Lefcheck et al. 2018, de los Santos et al. 2019, Orth et al. 2020); passive restoration may also be feasible for mangroves (Cameron et al. 2019).

Predicting coastal wetland restoration success and climate mitigation potential under climate change remains challenging; ecosystem responses to interactive climate stressors are not well-understood and future losses of blue carbon systems are likely (Short et al. 2016, FitzGerald & Hughes 2019, Lovelock & Reef 2020). Furthermore, coastal wetlands, especially seagrasses and salt marshes, remain inadequately mapped in many areas, creating uncertainty regarding the spatial extent, loss, and restoration of these ecosystems (McOwen et al. 2017, Xu et al. 2020). Additional research is needed to fully quantify the mitigation potential under future scenarios.

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that coastal wetland restoration has a technical potential of 0.04-0.84 $GtCO_2$-eq yr^{-1} (median 0.17) of which 0.05-0.20 $GtCO_2$-eq yr^{-1} is available at USD 100/tCO_2. There is *high confidence* (*robust evidence, high agreement*) that coastal wetlands, especially mangroves, contain large carbon stocks relative to other ecosystems and *medium confidence* (*medium evidence, medium agreement*) that restoration will reinstate pre-disturbance carbon sequestration rates. Uncertainties remain in quantifying the magnitude of the climate mitigation potential from coastal wetland restoration; however, there is *high confidence* (*robust evidence, high agreement*) that coastal wetland restoration will provide a suite of valuable co-benefits. Because of the many co-benefits, especially coastline protection, coastal wetland restoration can be considered 'no regrets' mitigation.

7.4.3 Agriculture

7.4.3.1 Soil carbon management in croplands and grasslands

Activities, co-benefits, risks and implementation opportunities and barriers. Increasing soil organic matter in croplands are agricultural management practices that include (1) crop management: for example, high input carbon practices such as improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology, (2) nutrient management (see Section 7.4.3.6), (3) reduced tillage intensity and residue retention, (4) improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid / semi-arid conditions, (5) improved rice management (see Section 7.4.3.5) and (6) biochar application (see Section 7.4.3.2) (Smith et al. 2014; 2019). For increased soil organic matter in grasslands, practices include (1) *management of vegetation*: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management, (2) *animal management*: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification, and (3) *fire management*: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning (Smith et al. 2014; 2019). Whilst there are co-benefits for livelihoods, biodiversity, water provision and food security (Smith et al. 2019), and impacts on leakage, indirect land-use change and foregone sequestration do not apply, the climate benefits of soil carbon sequestration in croplands can be negated if achieved through additional fertiliser inputs (potentially causing increased N_2O emissions), and both saturation and permanence are relevant concerns. When considering implementation barriers, soil carbon management in croplands and grasslands is a low-cost option at a high level of technology readiness (it is already widely deployed) with low socio-cultural and institutional barriers, but with difficulty in monitoring and verification proving a barrier to implementation (Smith et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Building on AR5, the SRCCL reported the global mitigation potential for soil carbon management in croplands to be 1.4–2.3 $GtCO_2$-eq yr^{-1} (Pradhan et al. 2013; Smith et al. 2008; 2014), though the full literature range was 0.3-6.8 (Conant et al. 2017; Dickie et al. 2014; Frank et al. 2017; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Henderson et al., 2015; Herrero et al. 2016; Paustian et al. 2016; Powlson et al. 2014; Sanderman et al. 2017; Smith 2016; Smith et al. 2016b; Sommer and Bossio 2014; Zomer et al. 2016; Roe et al. 2019). The global mitigation potential for soil carbon management in grasslands was assessed to be 1.4–1.8 $GtCO_2$-eq yr^{-1}, with the full literature range being 0.1-2.6 $GtCO_2$-eq yr^{-1} (Conant et al. 2017; Herrero et al. 2016; Smith et al. 2008, 2014; Roe et al. 2019). Lower values in the range represented economic potentials, whilst higher values represented technical potentials – and uncertainty was expressed by reporting the whole range of estimates. The SR1.5 outlined associated costs reported in literature to range from - 45 to 100 USD/tCO_2, describing enhanced soil carbon sequestration as a cost-effective measure (de Coninck et al. 2018). Despite significant mitigation potential, there is limited inclusion of soil carbon sequestration as a response option within IAM mitigation pathways (Rogeli et al. 2018).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). No recent literature has been published which conflict with the mitigation potentials reported in the SRCCL. Relevant papers include Lal et al. (2018) which estimated soil carbon sequestration potential to be 0.7-4.1 $GtCO_2$-eq yr^{-1} for croplands and 1.1-2.9 $GtCO_2$-eq yr^{-1} for grasslands. Bossio et al. (2020) assessed the contribution of soil carbon sequestration to natural climate solutions and found the potential to be 5.5 $GtCO_2$ yr^{-1} across all ecosystems, with only small portions of this (0.41 $GtCO_2$-eq yr^{-1} for cover cropping in croplands; 0.23, 0.15, 0.15 $GtCO_2$-eq yr^{-1} for avoided grassland conversion, optimal grazing intensity and legumes in pastures, respectively) arising from croplands and grasslands. Regionally, soil carbon management in croplands is feasible anywhere, but effectiveness can be limited in very dry regions (Sanderman et al. 2017). For soil carbon management is grasslands the feasibility is greatest in areas where grasslands have been degraded (e.g. by overgrazing) and soil organic carbon is depleted. For well managed grasslands, soil carbon stocks are already high and the potential for additional carbon storage is low. Available literature indicates economic (USD 100/tCO_2) mitigation potential ($MtCO_2$ yr^{-1}) for croplands and grasslands of 161 and 245 for Africa and the Middle East, 340 and 165 for Asia and developing Pacific, 211 and 254 for Developed Countries, 108 and 61 for Eastern Europe and West-Central Asia, and 103 and 168 for Latin America and the Caribbean for the period 2020-2050 (Table 7.5).

Critical assessment and conclusion. In conclusion, there is *medium confidence* that enhanced soil carbon management in croplands has a global technical mitigation potential of 0.4-6.7 $GtCO_2$ yr^{-1} (median 1.5), and in grasslands of 0.2-2.6 $GtCO_2$ yr^{-1} (median = 0.8) of which, 0.3 $GtCO_2$ yr^{-1} (median value) is estimated to be available in both categories at USD 100/tCO_2. Regionally, soil carbon management in croplands and grasslands is feasible anywhere, but effectiveness can be limited in very dry regions, and for grasslands it is greatest in areas where degradation has occurred (e.g. by overgrazing) and soil organic carbon is depleted. Barriers to implementation include regional capacity for monitoring and verification (especially in developing countries), and more widely through concerns over saturation and permanence.

7.4.3.2 Biochar

Activities, co-benefits, risks and implementation opportunities and barriers. Biochars are produced by thermal decomposition of organic matter in an oxygen-limited environment through pyrolysis or gasification (Lehmann and Joseph 2015). A wide range of biomass feedstocks can be used, including wood waste, garden waste, manure, biosolids and straw. Biochar is recognised as a carbon dioxide removal (CDR) strategy: the conversion of biomass to biochar stabilises carbon in a persistent form. When used as a soil amendment, biochar persistence is estimated at decades to thousands of years, depending on feedstock and production conditions (Singh et al. 2015; Wang et al. 2016). Biochars produced at higher temperatures (>~ 450°C) and from woody material persist longer in soil than those produced at lower temperatures (~300-450°C) or from manures (Singh et al. 2012; Budai et al. 2016; Wang et al. 2016). Biochar persistence is increased through interaction with clay minerals and native soil organic matter (Fang et al. 2015). Additional CDR benefits from biochar arise through "negative priming": biochar can enhance soil carbon stocks through stabilisation of rhizodeposits via sorption of dissolved organic C on biochar surfaces and formation of biochar-organo-mineral complexes (Archanjo et al. 2017; Hagemann et al. 2017; Weng et al. 2015, 2017; 2018; Wang et al. 2016). Besides CDR, additional climate change abatement through biochar systems can result from: avoided fossil fuels when pyrolysis gases, co-produced with biochar, are used for renewable heat or power; decrease in N_2O emissions from soil, although this impact varies widely (Cayuela et al. 2014; 2015; Song et al. 2016; He et al. 2017; Verhoeven et al. 2017; Borchard et al. 2019); reduced requirements for GHG-intensive nitrogen fertiliser, due to reduced losses of nitrogen through leaching and/or volatilisation (Liu et al. 2019; Borchard et al. 2019); and reduced GHG emissions from compost when biochar is added (Agyarko-Mintah et al. 2017; Wu et al. 2017a). When applied to paddy rice, biochar has been associated with substantial reductions (20-40% on average) in N_2O emissions (Song et al. 2016; Awad et al. 2018; Liu et al. 2018) (see also Section 7.4.3.5), and smaller reduction in CH_4 emissions, though effects vary between studies (Song et al. 2016; He et al. 2017; Kammann et al. 2017; Kim et al. 2017; Awad et al. 2018). As a feed additive for ruminant livestock there is some inconsistent evidence that biochar could reduce enteric CH_4 emissions (see Section 7.4.3.4).

Co-benefits of biochar vary between biochars and application contexts, and can include yield increase particularly in sandy and acidic soils with low cation exchange capacity (Woolf et al. 2016; Jeffery et al. 2017); enhanced soil water-holding capacity (Omondi et al. 2016); increased nitrogen use efficiency and reduced nutrient leaching and runoff (Liu et al. 2019; Borchard et al. 2019); enhanced biological nitrogen fixation (Van Zwieten et al. 2015); adsorption of organic pollutants and heavy metals, reducing plant uptake and environmental contamination (e.g. Silvani et al. 2019); odour reduction from manure handling and application (e.g. Hwang et al. 2018); and management of forest fuel loads, reducing wildfire risk (Puettmann et al. 2020). CDR through biochar application to soil amendment has high permanence and low risk of reversal. Other mitigation benefits vary depending on the context. Due to its dark colour biochar could decrease soil albedo (Meyer et al. 2012), but under recommended rates and application methods, involving incorporation, this is not likely to be significant. Barriers to upscaling biochar include the limited large-scale production facilities in most countries, high production costs when produced at small scale, and limited experience, knowledge, standardisation and quality control, that lead to lack of confidence amongst potential users (Gwenzi et al. 2015). Users need to be aware that biochar properties vary widely, depending on feedstock and production conditions, and should choose biochars that suit the application context, to optimise mitigation outcomes and production co-benefits.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Biochar was introduced as a mitigation option in the AR5 and is discussed as a CDR strategy in the SR1.5, however, consideration of potential was limited as biochar is not included in any IAMs. The SRCCL estimated the mitigation potential of biochar at 0.03-6.6 $GtCO_2$-eq yr^{-1} by 2050 (SRCCL, Chapters 2 and 4: Roberts et al. 2010; Pratt and Moran 2010; Powell and Lenton 2012; Hristov, *et al.*, 2013; Lee and Day, 2013; Lenton 2010; 2014; Dickie et al. 2014; Wolf et al. 2010; Smith et al. 2016; Griscom et al. 2017; Hawken 2017; Fuss et al. 2018) based on studies that varied widely in their assumptions, definition of potential, and scope of mitigation processes included. An analysis that applied biomass supply constraints to protect against food insecurity, loss of habitat and land degradation, estimated technical potential abatement at 3.7–6.6 $GtCO_2$-eq yr^{-1}, including 2.6–4.6 $GtCO_2$-eq yr^{-1} through CDR (Woolf et al. 2010), while Fuss et al. (2018) proposed a range of 0.5–2 $GtCO_2$-eq yr^{-1} as the sustainable potential for CDR through biochar.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Major developments since the SRCCL include insights on mechanisms contributing to 'negative priming', demonstrating the significance of interactions between biochar, soil minerals, microbes and plant carbon in the rhizosphere (DeCiucies et al. 2019; Fang et al. 2019). Recent research also highlights indirect climate benefits of biochars, associated with persistent yield response to biochar application (Kätterer et al. 2019; Ye et al. 2020); improved crop water use efficiency (Du et al. 2018; Gao et al. 2020); and reduced GHG and ammonia emissions from compost and manure handling when biochar is added, improving nitrogen retention (Sanchez-Monedero et al. 2018; Bora et al. 2020a; 2020b; Zhao et al. 2020). The close relationship between persistence and the H: Organic C ratio of biochar provides the basis for a simple method to estimate mitigation value of biochars, included as an optional component in the IPCC guidance for national greenhouse gas inventories (IPCC 2019). As the literature grows, a wide range of results, from positive to nil and occasionally negative impacts on growth, plant health and GHG emissions are being published. While this may suggest great uncertainty, it illustrates the natural, and expected variability (Lehmann and Rillig 2014), reflecting the reality that responses are dependent on the particular biochar applied, and the site-specific climatic and edaphic characteristics (Zygourakis, 2017). The key lesson is that biochar should be carefully selected, or "designer biochars" produced, to address the constraints of a particular site, in order to maximise the mitigation benefits (Mašek et al. 2019).

There are no published estimates of potential mitigation on a regional basis. However, disaggregation of global assessments (Table 7.5) suggest technical and economic (USD 100/tCO_2) potential (MtCO_2 yr^{-1}) respectively between 2020 and 2050 of; 84 and 25 for Africa and the Middle East, 394 and 118 for Asia and developing Pacific, 387 and 116 for Developed Countries, 57 and 17 Eastern Europe and West-Central Asia and 181 and 54 for Latin America and the Caribbean. Mitigation through biochar will be greatest where biochar is applied to responsive soils (acidic, low fertility), where soil N_2O emissions are high (intensive horticulture, irrigated crops), and where the syngas co-product is used to displace fossil fuels. Due to the early stage of commercialisation, some mitigation benefits are estimated from pilot-scale facilities, leading to uncertainty. However, the key contributor to mitigation is the long-term persistence of biochar carbon in soils, and this aspect has been widely studied, with rigorous and well-accepted methods using carbon isotopes to distinguish sources of respired CO_2 (e.g. Singh et al. 2012; Fang et al. 2019; Zimmermann and Ouyang, 2019). The overarching variable with greatest uncertainty is the availability of biomass for biochar production.

Critical assessment and conclusion. In summary, biochar has significant potential for climate change mitigation through CDR and emissions reduction, and can also improve soil properties, enhancing productivity and resilience to climate change (*medium agreement, robust evidence*), however the mitigation value and agronomic co-benefits depend strongly on the biochar properties, which are dependent on feedstock and biochar production conditions, and the soil to which biochar is applied (*strong agreement, robust evidence*). While biochar could provide moderate to large mitigation potential, it is not yet included in any IAMs, which has restricted comparison with other CDR strategies and development of mitigation approaches that integrate biochar with other land based CDR.

7.4.3.3 Agroforestry

Activities, co-benefits, risks and implementation opportunities and barriers. Agroforestry is a set of diverse land management systems that integrate woody biomass (including trees and woody shrubs) with crops and/or livestock in space and/or time. Agroforestry sequesters carbon in vegetation and soil (Nair *et al.*, 2010). Integration of woody biomass with crops and livestock offers benefits beyond carbon sequestration, including increased land productivity, diversified livelihoods, reduced soil erosion, restoration of degraded lands, reduced frequency and/or severity of dust storms, and more hospitable regional climates (Ellison *et al.*, 2017; Kuyah *et al.*, 2019; Mbow *et al.*, 2020). Planting trees haphazardly, however, can affect food production, disturb biodiversity, change local hydrology, and contribute to social inequality (Holl and Brancalion 2020, Amadu et al. 2020; Fleischman et al. 2020). In order to minimise risks and maximise co-benefits, agroforestry should be implemented as part of support systems that deliver tools, and information to increase farmers' agency. This may include, for example, reforming policies, strengthening extension systems, and creating market opportunities that enable adoption of agroforestry (Jamnadass et al. 2020, Sendzimir et al. 2011, Smith et al. 2019). Consideration of carbon sequestration amongst and within the palette of food, fuel, and environmental co-benefits within the farm, local, and regional contexts can further help support decisions to plant, regenerate and maintain agroforestry systems (Miller et al. 2020; Kumar and Nair 2011). In spite of the advantages, biophysical and socioeconomic factors can limit the adoption of agroforestry mitigation measures (Pattanayak *et al.*, 2003). Contextual factors may include, but are not limited to: water availability for crop establishment and growth, soil fertility, seed and germplasm access, land policies affecting farmer agency, access to credit to support investments in land, and access to information regarding the optimum species for a given location.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL estimated the global technical mitigation potential of agroforestry, with *medium confidence*, to be between 0.08 and 5.6 $GtCO_2$-eq yr^{-1} by 2050 (Griscom *et al.,* 2017; Dickie *et al.*, 2014; Zomer *et al.,* 2016; Hawken *et al.,* 2017). Estimates are derived from syntheses of potential area available for various agroforestry systems—e.g., windbreaks, farmer managed natural regeneration, and alley cropping and average annual rates of carbon accumulation. The cost-effective economic potential, also with *medium confidence*, is more limited at 0.3-2.4 $GtCO_2$-eq yr^{-1} (Zomer *et al.*, 2016; Griscom *et al.*, 2017; Roe *et al.*, 2019). Despite this potential, agroforestry is currently not considered in integrated assessment models used for mitigation pathways (Section 7.5).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent investigations and reviews have updated the estimate of global agroforestry technical mitigation potential and synthesised estimates of carbon sequestration across agroforestry systems. The most recent global analysis of agroforestry's mitigation potential estimates a technical potential of as high as 9.4 $GtCO_2$-eq yr^{-1} (Chapman *et al.*, 2020) assuming the conversion of 1.87 and 1.89 billion ha of crop and pasture lands to agroforestry, respectively. This estimate is at least 68% greater than the largest estimate reported in the SRCCL (Hawkes et al. 2017) and represents a new conservative upper bound because Chapman *et al.* (2020) only accounted for aboveground carbon while assuming vast implementation on crop and pasture lands. Considering both above- and belowground carbon of windbreaks, alley cropping and silvopastoral systems at a more limited areal extent (Griscom *et al.*, 2020), the economic potential of agroforestry was estimated to be only about 0.8 $GtCO_2$-eq yr^{-1}. Variation in estimates primarily result from assumptions on the agroforestry systems including, extent of implementation and estimates of carbon sequestration potential when converting to agroforestry.

Estimates of agroforestry mitigation potential typically report at the field or global scale; regional estimates are scant yet best fit agroforestry options can differ significantly regionally (Feliciano *et al.*, 2018). For example, multi-strata shaded coffee and cacao are successful in the humid tropics (Somarriba *et al.*, 2013; Blaser *et al.*, 2018), silvopastoral systems are prevalent in Latin American prairies (Peters *et al.*, 2013; Landholm *et al.*, 2019), and shelterbelts and windbreaks are common in Europe. At the field scale, agroforestry accumulates between 0.59 and 6.24 t ha^{-1} yr^{-1} of carbon aboveground. Belowground carbon stocks often constitute 25% or more of the total carbon in agroforestry production systems (De Stefano and Jacobson, 2017; Cardinael *et al.*, 2018). According to recent data, regional economic (at USD100/tCO_2-eq) mitigation potential ($MtCO_2$-eq yr^{-1}) is estimated to be about 180 in Africa and the Middle East, 370 in Asia and developing Pacific, 265 in Developed Countries, 180 in Eastern Europe and West-Central Asia, and 130 in Latin America and the Caribbean for the period 2020-2050 (Table 7.5).

Simultaneous to improved estimates of mitigation potential, recent work has also elaborated additional co-benefits and has more precisely identified implementation barriers. In addition to the aforementioned co-benefits, evidence now shows that agroforestry improves various aspects of soil health, including infiltration rates and structural stability (Muchane *et al.*, 2020); reduces ambient temperatures and crop heat stress (Sida *et al.*, 2018); increases groundwater recharge in drylands when managed at moderate density (Ilstedt *et al.*, 2016; Bargués-Tobella *et al.*, 2019); diversifies livelihood opportunities (Reppin *et al.*, 2019); positively influences human health outcomes (Rosenstock *et al.*, 2019); and can improve dietary diversity (McMullin *et al.*, 2019). Along with previously mentioned constraining factors, low social capital, assets, and labour availability have been identified as pertinent to the adoption of agroforestry techniques. Practically all constraining factors are interdependent and subject to the context of implementation (Arslan *et al.*, 2020).

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that agroforestry has a technical potential of 0.29 to 9.40 $GtCO_2$-eq yr^{-1} (median = 1.81), of which 51% (0.93 $GtCO_2$-eq yr^{-1}) is available at USD100/tCO_2. Despite uncertainty around global estimates due to regional preferences for various management systems, suitable land available, and growing conditions, there is *high confidence* in agroforestry's mitigation potential at the field scale. Crucially, the field scale is where land management decisions are made. With countless options for farmers and land managers to implement (and benefit) from agroforestry, there is *medium confidence* in the feasibility of agroforestry' mitigation potential regionally. Reaching these targets requires considering technology, market and policy constraints simultaneously. Efforts that match the diverse suite of agroforestry options--including species and management--to local biophysical and social context to land managers goals are the most likely to maximise mitigation and co-benefits and avoid unintended risks (Sinclair and Coe 2019).

Box 7.4 Case study: agroforestry in Brazil – CANOPIES

Summary

Brazilian farmers are integrating trees into their croplands in various ways, ranging from simple to highly complex agroforestry systems. While complex systems are more effective in the mitigation of climate change, trade-offs with scalability need to be resolved for agroforestry systems to deliver on their potential. The Brazilian-Dutch CANOPIES project (Steinfeld et al) is exploring transition pathways to agroforestry systems optimised for local ecological and socio-economic conditions

Background

The climate change mitigation potential of agroforestry systems is widely recognised (FAO 2017; Zomer et al. 2016) and Brazilian farmers and researchers are pioneering diverse ways of integrating trees into croplands, from planting rows of eucalyptus trees in pastures up to highly complex agroforests consisting of >30 crop and tree species. The degree of complexity influences the multiple functions that farmers and societies can attain from agroforestry: the more complex it is, the more it resembles a natural forest with associated benefits for its C storage capacity and its habitat quality for biodiversity (Santos et al. 2019). However, trade-offs exist between the complexity and scalability of agroforestry as complex systems rely on intensive manual labour to achieve high productivity (Tscharntke et al. 2011). To date, mechanisation of structurally diverse agroforests is scarce and hence, efficiencies of scale are difficult to achieve.

Case description

These synergies and trade-offs between complexity, multifunctionality and scalability are studied in the CANOPIES (*Co-existence of Agriculture and Nature: Optimisation and Planning of Integrated Ecosystem Services*) project, a collaboration between Wageningen University (NL), the University of São Paulo and EMBRAPA (both Brazil). Soil and management data are collected on farms of varying complexity to evaluate C sequestration and other ecosystem services, economic performance and labour demands.

Interactions and limitations

The trade-off between complexity and labour demand is less pronounced in EMBRAPA's integrated crop-livestock-forestry (ICLF) systems, where grains and pasture are planted between widely spaced tree rows. Here, barriers for implementation relate mostly to livestock and grain farmers' lack of knowledge on forestry management and financing mechanisms[5] (Gil et al. 2015). Additionally, linking these financing mechanisms to C sequestration remains a Monitoring, Reporting and Verification challenge (Smith et al., 2020).

Lessons

Successful examples of how more complex agroforestry can be upscaled do exist in Brazil. For example, on farm trials and consistent investments over several years have enabled Rizoma Agro to develop a citrus production system that integrates commercial and native trees in a large-scale multi-layered agroforestry system. The success of their transition resulted in part from their corporate structure that allowed them to tap into the certified Green Bonds market (CBI, 2020). However, different transition strategies need to be developed for family farmers and their distinct socio-economic conditions.

7.4.3.4 Enteric fermentation

Activities, co-benefits, risks and implementation opportunities and barriers. Mitigating CH_4 emissions from enteric fermentation can be direct (i.e. targeting ruminal methanogenesis and emissions per animal or unit of feed consumed) or indirect, by increasing production efficiency (i.e. reducing emission intensity per unit of product), and can be classified as measures relating to (1) feeding, (2) supplements, additives and vaccines, and (3) livestock breeding and wider husbandry (Jia et al. 2019). Co-benefits include enhanced climate change adaptation and increased food security associated with improved livestock breeding (Smith et al. 2014). Risks include mitigation persistence, ecological impacts associated with improving feed quality and supply, or potential toxicity and animal welfare issues concerning feed additives. Implementation barriers to achieving this technical potential include feeding/administration constraints, the stage of development of measures (e.g. anti-methanogen vaccines and inhibitors), legal restrictions on emerging technologies and negative impacts, such as those previously described as risks (Smith et al. 2014; Jia et al. 2019; Smith et al. 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 indicated medium (5-15%) technical mitigation potential from both feeding and breeding related measures (Smith et al. 2014). More recently, and by compiling values from multiple studies that used differing GWP_{100} values, the SRCCL estimated with *medium confidence*, a global mitigation potential of 0.12-1.18 $GtCO_2$-eq yr^{-1} 0.12-1.18 $GtCO_2$-eq yr^{-1} between 2020 and 2050, with the range reflecting technical, economic and sustainability constraints (SRCCL, Chapter 2: Hristov, et al., 2013; Dickie et al. 2014; Herrero et al. 2016; Griscom et al. 2017). The underlying literature uses a mixture of IPCC GWP_{100} values for CH_4, preventing conversion of estimates to CH_4. These studies derived estimates from *in vivo* research data, regional case studies and synthesis of previously published estimates, considering a wide range of measures and implementation constraints (technical and economic). Improved livestock feeding and breeding were included in IAM emission pathway scenarios within the SRCCL and SR1.5, though it was suggested that the full mitigation potential of enteric CH_4 measures is not captured in current models (Rogelj et al. 2018; de Coninck et al. 2018).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies generally identify the same measures as those outlined in the SRCCL, with the addition of early life manipulation of the ruminal biome (Grossi et al. 2019; Beauchemin et al. 2020; Eckard and Clark 2020; Thompson and Rowntree 2020). There is robust evidence and high agreement that chemically synthesised inhibitors are promising emerging near-term measures (Patra et al. 2016; Jayanegara et al. 2017; Van Wesemael et al. 2019; Beauchemin et al. 2020) with high (e.g. 16-70% depending on study) mitigation potential reported (e.g. Hristov et al. 2015; McGinn et al. 2019; Melgar et al. 2020) and commercial availability expected within five years. However, their mitigation persistence (McGinn et al. 2019), cost (Carroll and Daigneault 2019; Alvarez-Hess et al. 2019) and public acceptance

(Jayasundara et al. 2016) is currently unclear; administration in pasture-based systems is likely to be challenging (Patra et al. 2017; Leahy et al. 2019). Research into other promising inhibitors/feeds containing inhibitory compounds, such as macroalga or seaweed (Changas et al. 2019; Kinley et al. 2020; Roque et al. 2019), shows promise, although concerns have been raised regarding palatability, toxicity, environmental impacts and the development of industrial-scale supply chains (Beauchemin et al. 2020; Eckard and Clark 2020). In the absence of CH_4 vaccines, which are still under development (Carroll and Daigneault 2019; Eckard and Clark 2020), pasture-based and non-intensive systems remain heavily reliant on increasing production efficiency (Beauchemin et al. 2020). Breeding of low emitting animals may play an important role and is a subject under on-going research (Pickering et al. 2015: Jonker et al. 2018; López-Paredes et al. 2020).

Approaches differ regionally, with more focus on direct, technical options in developed countries, and improved efficiency in developing countries (Caro et al. 2016; Mottet et al. 2017; Frank et al. 2018; MacLeod et al. 2018). Disaggregation of global assessments (Section 7.4.1.) indicate economic (at USD100/tCO_2-eq) potential (Mt CO_2 yr^{-1} using GWP_{100} with a combination of IPCC values for CH_4) for the period 2020-2050 of; 19 for Africa and the Middle East, 33 for Asia and developing Pacific, 26 for Developed Countries, 2 for Eastern Europe and West-Central Asia and 19 for Latin America and the Caribbean (Table 7.5). Despite numerous country and sub-sector specific studies, most of which include cost analysis (Hasegawa and Matsuoka 2012; Hoa et al. 2014; Jilani et al. 2015; Eory et al. 2015; Hasegawa and Matsuoka 2015; Pradhan et al. 2017; Pellerin et al. 2017; Eriksen and Crane 2018; Habib and Khan 2018; Kashangaki and Ericksen 2018; Salmon et al. 2018; Brandt et al. 2019; Carroll and Daigneault 2019; Dioha and Kumar 2019; Kiggundu et al. 2019; Lanigan et al. 2019; Leahy et al. 2019; Mosnier et al. 2019; Pradham et al. 2019; Sapkota et al. 2019), sectoral assessment of regional technical and notably economic (Beach et al. 2015; EPA 2019) potential is restricted by lack comprehensive and comparable data. Therefore, verification of regional estimates indicated by global assessments is challenging. Feed quality improvement, which may have considerable potential in developing countries (Caro et al. 2016; Mottet et al. 2017), may have negative wider impacts. For example, potential land use change and greater emissions associated with production of concentrates (Brandt et al. 2019), with evaluation by Life Cycle Assessment suggested before implementation (Beauchemin et al. 2020).

Critical review and conclusion. Based on studies to date, using GWP_{100} with a mixture of IPCC values for CH_4, there is *medium confidence* that activities to reduce enteric CH_4 emissions have a technical potential of 0.7-1.2 GtCO_2-eq yr^{-1} (median = 0.9) globally, of which, approximately 0.2 GtCO_2-eq yr^{-1} is available at USD100/tCO_2. Lack of comparable country and sub-sector studies to assess the context applicability of measures, associated costs and realistic adoption likelihood, prevents verification of global and regional mitigation estimates. The CO_2-eq value may also slightly differ if the GWP_{100} IPCC AR6 CH_4 value was uniformly applied within calculations.

7.4.3.5 Improve rice management

Activities, co-benefits, risks and implementation opportunities and barriers. Emissions from rice cultivation mainly concern CH_4 associated with anaerobic conditions though N_2O emission also occur via nitrification and denitrification processes. Measures to reduce CH_4 and N_2O emissions include (1) improved water management (e.g. single drainage and multiple drainage practices), (2) improved residue management and (3) improved fertiliser application (e.g. slow release fertiliser and nutrient specific application) and soil amendments (including biochar and organic amendments) (Pandey et al. 2014; Kim et al. 2017; Yagi et al. 2019; Sriphirom et al. 2020). These measures not only have mitigation potential but can enhance system sustainability (Box 7.5), potentially reducing water used and increasing farm income (Jat et al., 2015, Sriphirom et al. 2019). However, in terms of mitigation of CH_4 and N_2O, antagonistic effects can occur, whereby water management can enhance N_2O emissions due to induction of aerobic condition (Sriphirom et al. 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The AR5 identified emission from rice cultivation of 0.49-0.723 Gt CO_2-eq yr^{-1} in 2010 with the average annual growth of 0.4% yr^{-1}. The SRCCL estimated a global mitigation potential from improved rice cultivation of 0.08-0.87 Gt CO_2-eq yr^{-1} between 2020 and 2050, with the range representing the difference between technical and economic constraints, types of activities included (e.g. improved water management and straw residue management) and GHGs considered (SRCCL, Chapter 2: Dickie et al. 2014; Poustian et al. 2016; Beach et al. 2015; Grissom et al. 2017; Hawken 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since AR5 and SRCCL, studies on mitigation potential have focused on water and nutrient management practices with the aim of improving overall sustainability. Recent studies that explore site-specific emissions, have helped improve the resolution of regional estimates. Intensity of emissions show considerable spatial and temporal variation being dependent on-site specific factors including degradation of soil organic matter, management of water levels in the field, the types and amount of fertilisers applied, rice variety and local cultivation practices. Variation in CH_4 emissions have been found to range from 0.5-41.8 mg/m2/hr in Southeast Asia (Sander et al. 2014; Chistahisong et al. 2018; Setyanto et al. 2018; Sibayan et al. 2018; Wang et al. 2018; Maneepitak et al. 2019), 0.5-37.0 mg/m^2/hr in Southern and Eastern Asia (Zhang et al. 2010; Wang et al. 2012; Oo et al, 2018; Wang et al. 2018; Takakai et al. 2019) and 0.5-10.4 in North America (Wang et al. 2018). Current studies on emissions of N_2O also showed high variation at the range of 0.13-654 ug/m2/hr (Akiyama et al. 2005; Islam et al. 2018; Kritee et al. 2018; Oo et al. 2018; Zschornack et al. 2018).

Recent studies have highlighted the potential of water management to mitigate GHG emissions, while also enhancing water use efficiency. A meta-analysis on multiple drainage systems found that Alternative Wetting and Drying (AWD) with irrigation management, can reduce CH_4 emissions by 20-30% and water use by 25.7 %, though resulted in a slight yield reduction (5.4%) (Carrijo et al. 2017). Water management for both single and multiple drainage can (most likely) reduce methane emission by ~35 % but increase nitrous oxide by ~ 20% (Yagi et al. 2019). However, N_2O emissions occur only under dry conditions, therefore total reduction in terms of net GWP is ~ 30%. Emissions of N_2O are higher during dry seasons (Yagi et al. 2019) and depend on site specific factors as well as the quantity of fertiliser and organic matter inputs into the paddy rice system. Variability of N_2O emissions from single and multiple drainage can range from 0.06-33 kg/ha (Hussain 2014; Kritee 2018). Overall, the economic (<USD 100/tCO_2-eq) mitigation potential (Mt CO_2-eq yr^{-1} using GWP_{100} IPCC AR6 values) is estimated to be 7-10 for Africa and the Middle East, 139-156 for Asia and developing Pacific, 4-7 for Developed Countries, 0 for Eastern Europe and West-Central Asia, and 6-3 for Latin America and the Caribbean from rice cultivation measures during the period 2030-2050 (Table 7.5).

Critical assessment and conclusion. Improving rice cultivation practices will not only reduce GHG emissions, but also but improve production sustainability in terms of resource utilisation including water consumption and fertiliser application. However, emission reductions show high variability and are based site specific conditions and cultivation practices. Based on studies to date, there is *high confidence* that improved rice management has a technical potential of 0.12-0.81 GtCO_2-eq yr^{-1} (median = 0.24) of which 0.12 GtCO_2-eq yr^{-1} is available at USD 100/tCO_2.

Box 7.5 Case study: sustainable rice management

Summary

Improve of rice management has been shown to have high mitigation potential in Asia and developing Pacific (Griscom et al. 2020). Water management and improved nutrient use efficiency can not only deliver mitigation but can enhance drought adaptation and promote sustainable development. Although practices of single and multiple drainage, including alternative wetting and drying (AWD) have been found not to impact rice yields, therefore increasing adoption likelihood by farmers, trade-offs between CH_4 and N_2O during the drying period may off-set some benefits. Achievement of mitigation through improved rice cultivation requires policy support s as well as improved knowledge exchange among farmers.

Background

Rice systems provide food for more than 3.5 billion people with more than 50 kg of rice consumed per capita per year globally and 90% of the global rice production taking place in Asia. It is expected that rice cultivation needs to increase by 46 % by the end of 2030 to meet the increasing demand from a growing global population (FAO 2014). Rice production forms a considerable emissions source, with associated CH_4 emissions estimated to account for 24% of AFOLU CH_4 emissions and 9% of total AFOLU GHG emissions in 2018 (see Section 7.2). However, there are a number of promising mitigation options that can also improve overall production sustainability.

Implementation in Vietnam

Vietnam is among the top five global rice exporters. Rice is grown throughout the country with irrigated production accounting for around 80% of the rice area. Improved water management in terms of AWD was officially introduced to rice farmers by local government in 2005 as part of the 1M5R (One must do 5 reduction) agrarian campaign that aimed to increase the efficiency of rice cultivation (Lampayan et al. 2015). The safe AWD concept, referring to 5 cm of water level in the field and 15 cm dry below the soil surface and indicated by plastic pipes, was introduced.

An Giang was the first province to adopt AWD in 2009 with AWD practiced on 18% of the total rice cultivation area. In 2015, the diffusion rate increases to 52%, with 54% of farmers households adopting AWD (Yamaguchi et al. 2019). In addition, some communes of Phu Tan and Cho Moi districts had more than 75% AWD adoption rate in 2015. However, there are some communes in the Tri Ton district including Ba Chuc and Tan Tuyen where the AWD adoption rate has declined due to restriction factors including different percolation and seepage rates resulting from the different elevations of paddy plots and fluctuation in precipitation, agro-engineering factors including density and quality of water canals, pump ownership status and paddy surface level and social factors including farmer understanding of AWD, contracted paddy cultivation and synchronising water management with neighbouring plots (Yamaguchi et al. 2017). Quynh and Sander (2015) identified additional barriers such as poor irrigation systems, level and size of rice field, different type of soil, conflict on benefits between farmers and pumping stations etc.

GHG reduction and water use

Rice cultivation under AWD including, safe AWD and site specific AWD (AWDS) in Huong Tra district, Thua Thien Hue Province, was found to reduce CH_4 and N_2O emissions by 29% to 30% and 26% to 27% respectively with the combination of net GWP about 30% as compared to continuous flooding (Tan et al. 2018). Water use was also reduced by 15%. Additionally, the system increased water productivity from 0.556 kg grain m^{-3} to 0.727 kg grain m^{-3}, representing a 31% increase.

Impact on yield and cost

Over three years, grain yields were 10-11% higher in fields with AWD compared to conventional fields in Thua Thien Hue Province (Tran et al. 2018). Yield increases vary according to season. Implementation of AWD systems in dry season were found to increase yields by 6-15 % in An Giang Province (Ha et al. 2014) while during the spring and summer seasons at Nam Sach district, Hai Duong province, yield increases of 8 % and 20 % were observed respectively, when compare to conventional practice (Quynh and Sander 2015). The higher yields may have resulted from reduced incidence of plant disease, insect damage and poor grain filling, as well as promotion of root spread (Yamaguchi et al. 2017).

In terms of economic benefits, farm income was estimated to increase by 22% due to a reduction in production costs including seed (14%), pesticide (35%), pumping and labour (5%), while fertiliser costs increased by 12% (Quynh and Sander 2015). In addition, farmers can save the pumping cost and harvest cost (Yamaguchi et al. 2017). The economic benefit depends on many factors including site specific constrains and farmer's practice related to their understanding.

Interactions and limitations

Mitigation by improving rice management is based on water level and therefore, anaerobic condition management. However, this can induce aerobic conditions and cause nitrification and denitrification processes leading to increased N_2O emissions. Trade-offs between CH_4 and N_2O mitigation is therefore a potential limitation. Lack of appropriate irrigation system, the small size of rice fields and conflict in water used among farmers may act as barriers to implementation.

Lessons

Mitigation with no impact on rice yield is preferable to farmers but needs promotion by government.

Co-benefits in term of improved farm income, water used efficiency and nutrient management can be achieved in conjunction with GHG mitigation. Overcoming barriers such as agricultural engineering factors (e.g. irrigation systems, specific soil properties) and social factors (farmers' understanding), is key to ensuring successful implementation.

7.4.3.6 Crop nutrient management

Activities, co-benefits, risks and implementation opportunities and barriers. Improved crop nutrient management can reduce N_2O emissions from cropland soils. Practices include optimising fertiliser application delivery, rates and timing, optimising the use of different fertiliser types (i.e. organic manures, composts and synthetic forms), using slow or controlled-released fertilisers or nitrification inhibitors (Smith et al. 2014; Griscom et al. 2017; Smith et al. 2019). In addition to individual practices, integrated nutrient management that combines crop rotations, reduced tillage, use of cover crops, manure application, soil testing and comprehensive nitrogen management plan, is suggested as central for optimising fertiliser use and enhancing nutrient uptake (Bationo et al. 2012; Lal et al. 2018). Such practices may generate additional mitigation by indirectly reducing synthetic fertiliser manufacturing requirements and associated emissions, though such mitigation is accounted for in the Industry Sector and not considered in this chapter (Tables 7.4 and 7.5). Co-benefits of improved nutrient management can include enhanced soil quality (notably when manure, crop residues or compost is utilised), carbon sequestration in soils and biomass, soil water holding capacity, adaptation capacity, crop yields, farm incomes, water quality (from reduced nitrate leaching and eutrophication) air quality (from reduced ammonia (NH_3) emissions) and in certain cases, may facilitate land sparing (Sapkota et al. 2014; Johnston and Bruulsema 2014; Smith et al. 2019; Mbow et al. 2019). A potential risk is reduced yields and implementation of practices should consider current soil nutrient status. Additionally, depending on context, practices may be inaccessible, expensive or required expertise to implement (Hedley 2014; Benson and Mogues 2018) while impacts of climate change may impact nutrient use efficiency (Amouzou et al. 2019) and therefore, mitigation potential.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL broadly identified the same practices as outlined in AR5 and estimated that improved cropland nutrient management could mitigate between 0.03 and 0.71 Gt CO_2-eq yr^{-1} between 2020 and 2050 (SRCCL Chapter 2: Dickie et al. 2014; Beach et al. 2015; Paustian et al. 2016; Griscom et al. 2017; Hawken, 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Research since the SRCCL highlights the mitigation potential and co-benefits of adopting improved nutrient management strategies, notably precision fertiliser application methods, and applicability in both large-scale mechanised and small-scale systems (USEPA 2019; Griscom et al. 2020; Aryal et al. 2020, Tian et al 2020). Improved crop nutrient management is feasible in all regions, but effectiveness is context dependent. Sub-Saharan Africa has one of the lowest global fertiliser consumption rates, with increased fertiliser use suggested as necessary to meet projected future food requirements (Mueller et al. 2012). Fertiliser use in Developed Countries is already high (Figure 7.11) with increased nutrient use efficiency likely to be among the most promising mitigation measures (Roe et al. 2019). Considering that Asia and developing Pacific, and Developed Countries accounted for the greatest share of global nitrogen fertiliser use, it is not surprising that these regions are estimated to have greatest economic (up to USD 100/tCO_2-eq) mitigation potential (17-304 MtCO_2-eq yr^{-1} and 7-67 MtCO_2-eq yr^{-1} respectively - using GWP_{100} and a combination of values for N_2O) between 2020 and 2050 (Table 7.5).

Critical assessment and conclusion. The overall estimated technical mitigation potential of 0.1-0.7 GtCO_2-eq yr^{-1} (median = 0.1) is roughly in line with that reported in the SRCCL (Jia et al. 2019). This value is based on GWP_{100} using a mixture of IPCC values for N_2O and may slightly differ if calculated using AR6 values. Approximately 0.1 GtCO_2-eq yr^{-1} is estimated to be available at up to USD 100/tCO_2 (*medium confidence*) (Table 7.5).

Box 7.6 Case study: the climate-smart village approach

Summary

The climate-smart villages (CSV) approach aims to generate local knowledge, with the involvement of farmers, researchers, practitioners, and governments, on climate change adaptation and mitigation while improving productivity, food security, and farmers' livelihoods (Aggarwal et al. 2018). This knowledge feeds a global network that includes 36 climate-smart villages in South and Southeast Asia, West and East Africa, and Latin America.

Background

It is expected that agricultural production systems across the world change in response to climate change, posing significant challenges to the livelihoods and food security of millions of people (IPCC 2014). Maintaining agricultural growth while minimising climate shocks is crucial to building a resilient food production system and meeting sustainable development goals in vulnerable countries.

Case description

The CSV approach seeks an integrated vision so that sustainable rural development is the final goal for rural communities. At the same time, it fosters the understanding of climate change with the implementation of adaptation and mitigation actions, as much as possible. Rural communities and local stakeholders are the leaders of this process, where scientists facilitate their knowledge to be useful for the communities and learn at the same time about challenges but also the capacity those communities have built through time. The portfolio includes weather-smart activities, water-smart practices, seed/breed smart, carbon/nutrient-smart practices, and institutional/market smart activities.

Interactions and limitations

The integration of technologies and services that are suitable for the local conditions resulted in many gains for food security and adaptation and for mitigation where appropriate. It was also shown that, in all regions, there is considerable yield advantage when a portfolio of technologies is used, rather than the isolated use of technologies (Govaerts et al. 2005; Zougmore et al. 2014). Moreover, farmers are using research results to promote their products as climate-smart leading to increases in their income (Acosta-Alba et al. 2019). However, climatic risk sites and socioeconomic conditions together with a lack of resource availability are key issues constraining agriculture across all five regions.

Lessons

1. Understanding the priorities, context, challenges, capacity, and characteristics of the territory and the communities regarding climate, as well as the environmental and socioeconomic dimensions, is the first step. Then, understanding climate vulnerability in their agricultural systems based on scientific data but also listening to their experience will set the pathway to identify climate-smart agriculture (CSA) options (practices and technologies) to reduce such vulnerability.
2. Building capacity is also a critical element of the CSV approach, rural families learn about the practices and technologies in a neighbour's house, and as part of the process, families commit to sharing their knowledge with other families, to start a scaling-out process within the communities. Understanding the relationship between climate and their crop is key, as well as the use of weather forecasts to plan their agricultural activities.
3. The assessment of the implementation of the CSA options should be done together with community leaders to understand changes in livelihoods and climate vulnerability. Also, knowledge appropriation by community leaders has led to farmer-to-farmer knowledge exchange within and outside the community (Ortega and Martínez-Barón 2018b).

7.4.3.7 Manure management

Activities, co-benefits, risks and implementation opportunities and barriers. Manure management measures aim to mitigate CH_4 and N_2O emissions from manure storage and deposition. Mitigation of N_2O considers both direct and indirect (i.e. conversion of ammonia (NH_3) and nitrate (NO_3^-) to N_2O) sources. According to the SRCCL, measures may include (1) anaerobic digestion, (2) applying nitrification or urease inhibitors to stored manure or urine patches, (3) composting, (4) improved storage and application practices, (5) grazing practices and (6) alteration of livestock diets to reduce nitrogen excretion (Mbow et al. 2019; Jai et al. 2019). Implementation of manure management with other livestock and soil management measures can enhance system resilience, sustainability, food security and help prevent land degradation (Smith *e*t al. 2014; Smith et al. 2019; Mbow et al. 2019), while potentially benefiting the localised environment, for example, regarding water quality (Di and Cameron 2016). Increased N_2O emission from the application of manure to poorly drained or wet soils is a potential risk associated with some measures.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 reported manure measures to have high (> 10%) mitigation potential. The SRCCL outlined a technical global mitigation potential between 2020 and 2050 of 0.01-0.26 Gt CO_2-eq yr^{-1} was estimated, with the range depending on economic and sustainable potential (SRCCL, Chapter 2: Dickie et al. 2014; Herrero et al. 2016). Conversion of estimates to native units is restricted as a mixture of GWP_{100} values were used in underlying studies. Measures were typically more suited to confined production systems (Jai et al. 2019; Mbow et al. 2019), while improved manure management is considered within IAM emission pathways (Rogeli et al. 2018).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Research published since SRCCL broadly focuses on measures relevant to intensive or confined systems (e.g. Kavanagh et al. 2019; Hunt et al. 2019; Sokolov et al. 2020; Im et al. 2020; Adghim et al. 2020; Mustafa et al. 2020), identifying other co-benefits and risks. For example, measures may enhance nutrient recovery, fertiliser value (Sefeedpari et al. 2019; Ba et al. 2020; Yao et al. 2020) and secondary processes such as biogas production (Shin et al. 2019). However, greenhouse gas and NH_3 mitigation can be antagonistic without appropriate management (Grossi et al. 2019; Aguirre-Villegas et al. 2019; Kupper et al. 2020; Ba et al. 2020), while high implementation costs may prevent adoption, notably of anaerobic digestion (Liu and Liu, 2018; Niles and Wiltshire 2019; Ndambi et al. 2019; Ackrill and Abdo 2020; Adghim et al. 2020). Nitrification inhibitors have been found to be effective at reducing N_2O emissions from pasture deposited urine (López-Aispún et al. 2020), although the use of nitrification inhibitors is restricted in some jurisdictions due to concerns around residues in food products (Di and Cameron, 2016; Eckard and Clark, 2020). Some fodder crops may naturally contain inhibitory substances (Simon et al. 2019; 2020; deKlain et al. 2020), though warrants further research (Podolyan et al. 2019; Gardiner et al. 2020).

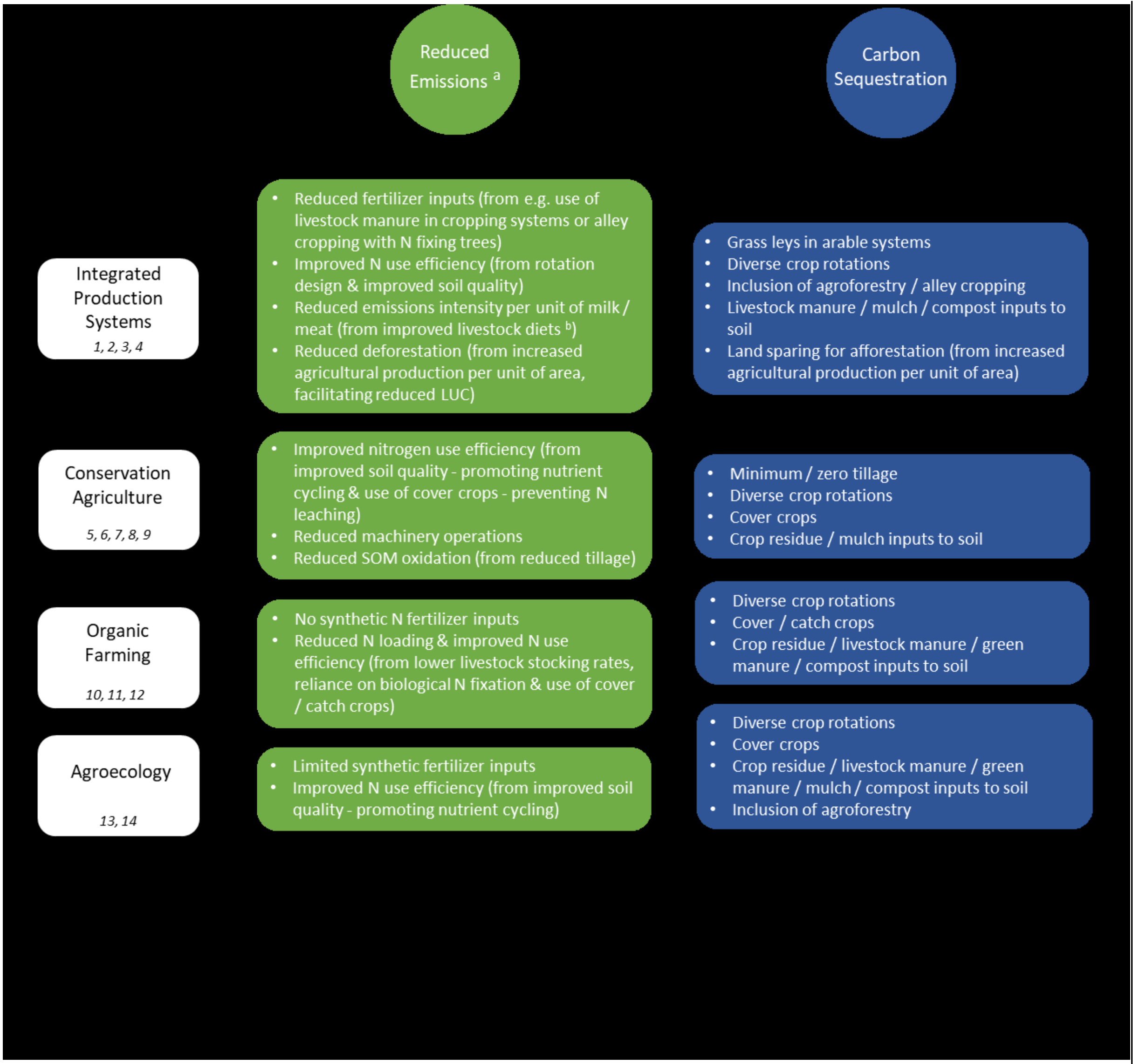
Country specific studies provide insight into regionally applicable measures, with emphasis on small-scale anaerobic digestion (e.g. dome digesters), solid manure coverage and daily manure spreading in Asia and the developing Pacific, and Africa (Hasegawa and Matsuoka 2012; Hoa et al., 2014; Jilani et al., 2015; Hasegawa and Matsuoka, 2015; Hasegawa et al. 2016; Padhan et al. 2017; Eriksen and Crane 2018; Padhan et al. 2019; Kiggundu et al. 2019; Dioha and Kumar 2019). Tank/lagoon covers, large-scale anaerobic digestion, improved application timing, nitrogen inhibitor application to urine patches, soil-liquid separation, reduced livestock nitrogen intake, trailing shoe, band or injection slurry spreading and acidification are emphasised in developed countries (Kaparaju and Rintala 2011; Eory et al. 2015; Jayasundara et al. 2016; Pape et al. 2016; Liu and Liu 2018; Pellerin et al. 2017; Lanigan et al. 2018; Carroll and Daigneault 2019; Eckard and Clark 2020). As with enteric fermentation (see Section 7.4.3.4), verification of regional mitigation estimates from disaggregation of global assessments is challenging. Global assessments (Table 7.5) indicate potential (Mt CO_2-eq yr^{-1} using GWP_{100} and a range of IPCC values for CH_4 and N_2O) of; 1 in Africa and the Middle East, 33 in Asia and developing Pacific, 81 in Developed Countries, 1 in Eastern Europe and West-Central Asia and 2 in Latin America and the Caribbean, for the period 2020-2050.

Critical assessment and conclusion. There is *medium confidence* that manure management measures have a mitigation potential of 0.3-0.5 $GtCO_2$-eq yr^{-1}, with 0.01-0.1 $GtCO_2$-eq yr^{-1} estimated to be available at USD 100/tCO_2. As with other non-CO_2 GHG mitigation estimates, values may slightly differ if IPCC AR6 GWP_{100} values for CH_4 and N_2O were used in calculations. There is *robust evidence and high agreement* that measures are applicable in all regions, with notable potential in developed countries associated with more intensive and confined production systems.

Box 7.7. Farming system approaches and mitigation

Introduction

The mitigation measures described within Section 7.4.3, largely form individual management practices that can be applied under various farming contexts. However, several system approaches to farming incorporate multiple mitigation measures that may also deliver important environmental co-benefits. There is *robust evidence* and *high agreement* that agriculture needs to change to facilitate environment conservation while increasing production. This box assesses evidence on the mitigation capacity of commonly applied and promoted systems approaches. These approaches are not necessarily mutually exclusive, may share similar principles or techniques and can be complimentary. In all cases, mitigation may result from either (1) emission reductions or (2) enhanced carbon sequestration, via combinations of management practices as outlined in Figure 1 within this Box.



Box 7.7, Figure 1 Potential mitigation mechanisms and associated management practices

Is there evidence that these approaches deliver mitigation?

Integrated Production Systems (IPS)

The integration of different enterprises in space and time (e.g. diversified cropping, crop and livestock production, agroforestry), therefore facilitating interaction and transfer of recourses between systems, is suggested to enhance sustainability and adaptive capacity (Hendrickson et al. 2008; Franzluebbers et al. 2014: Lemaire et al. 2014; Weindl et al. 2015; Gill et al. 2017; Olssen et al. 2019; Peterson et al. 2020; Walkup et al. 2020; Garrett et al. 2020). Research indicates some mitigation potential, including by facilitating sustainable intensification, though benefits are likely to be highly context specific (e.g. Herrero et al. 2013; Carvalho et al. 2014; Rosenstock et al. 2014; Piva et al. 2014; Weindle et al. 2015; Thornton and Herrero, 2015; de Figueredo et al. 2017; Lal 2020; Guenet et al. 2020). The systems outlined in the following discussion may form, or facilitate, IPS.

Conservation Agriculture (CA)

The SRCCL noted both positive and inconclusive results regarding CA and soil carbon, with sustained sequestration dependent on productivity and residue returns (Jai et al. 2019; Mirzabaev et al. 2019; Mbow et al. 2019). Recent research is in broad agreement, highlighting impacts of climate (Corbeels et al. 2019; Ogle et al. 2019; Gonzalez-Sanchez et al. 2019; Corbeels et al. 2020) with greatest mitigation potential suggested in dry regions (Sun et al. 2020). Theoretically, CA may facilitate improved nitrogen use efficiency (Lal 2015; Powlson et al. 2016) (*limited evidence*), though CA has mixed effects on soil N_2O emission (Six et al. 2004; Mei et al. 2019). CA is noted for its adaptation benefits, with *wide agreement* that CA can enhance system resilience to climate related stress, notably in dry regions. There is evidence that CA can contribute to mitigation, but its contribution is depended on multiple factors including climate and residue returns (*high confidence*).

Organic Farming (OF)

Several studies have explored emissions or the carbon footprint of organic compared to conventional systems (e.g. Nemecek et al. 2011; Skinner et al. 2014; Seufert and Ramankutty et al. 2017; Clark and Tilman, 2017). Evidence suggests a tendency for organic production to have lower emissions per unit of area and higher emissions per unit of product, though results vary and are context specific (*high confidence*). Fewer studies consider impacts of large-scale conversion to organic production globally. Though context specific (Seufert and Ramankutty 2017), OF is reported to typically generate lower yields (Seufert et al. 2012; de Ponti et al. 2012; Kirchmann 2019; Biernat et al. 2020). Large-scale conversion from conventional to organic production, without fundamental changes in food systems (Muller et al. 2017), may lead to increases in absolute emissions from land use change, driven by greater land requirements to maintain production (e.g. Leifeld 2016; Meemken and Qaim, 2018; Smith et al. 2019). OF may have mitigation capacity in certain instances though impacts of large-scale conversion requires further research.

Agroecology (AE) (including Regenerative Agriculture - RA)

There is limited discussion on the mitigation potential of AE (Gliessman 2013; Altieri and Nichollas 2017), but *robust evidence* that AE can improve system resilience and bring multiple co-benefits (Altieri et al. 2015; Mbow et al. 2019; Aguilara et al. 2020; Tittonell, 2020; Wagner et al. 2020) (see Box AGROECO in the IPCC WGII contribution to AR6). *Limited evidence* concerning the mitigation capacity of AE at a system level (Saj et al. 2017) makes conclusions difficult, yet studies into specific practices that may be incorporated, suggest AE may have mitigation potential (see Section 7.4.3) (*medium confidence*). However, AE which can incorporate management practices used in OF, may result in reduced yields, driving compensatory agricultural production elsewhere. Research into GHG mitigation by AE as a system and impacts of its wide-scale implementation is required. Despite absence of a universally accepted definition (Box 7.2), RA is gaining increasing attention and shares principles of AE. Some descriptions include carbon sequestration as a specific aim (Elevitch et al. 2018). Few studies have assessed mitigation potential of RA at a system level (e.g. Colley et al. 2019). Like AE, it is *likely* that RA can contribute to mitigation, the extent to which is currently unclear and by its case-specific design, will vary (*medium confidence*).

Box 7.8. Case study: Mitigation Options and Costs in the Indian Agricultural Sector

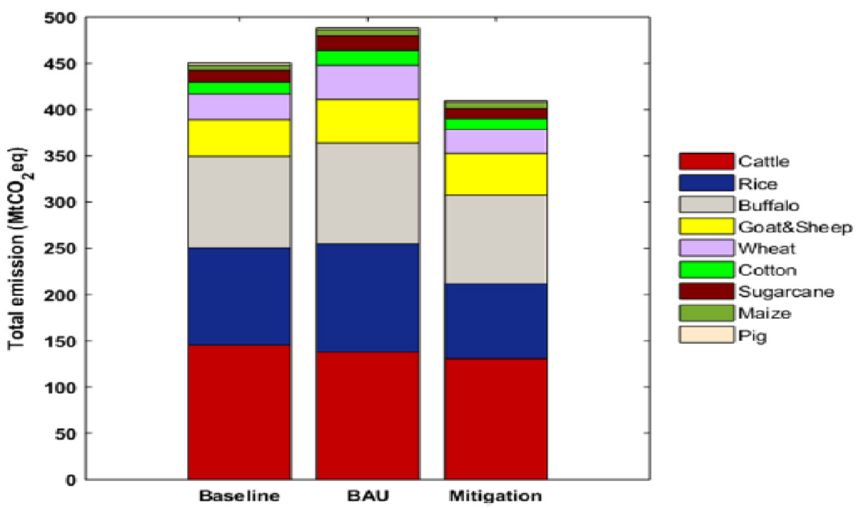
Objective

To assess the technical mitigation potentials of Indian agriculture and costs under a Business as Usual scenario (BAU) and Mitigation scenario up to 2030 (Sapkota et al. 2019).

Results

The study shows that by 2030 under BAU scenario GHG emissions from the agricultural sector in India would be 515 $MtCO_2$-eq yr^{-1} (using GWP_{100} and IPCC AR4 values) with a technical mitigation potential of 85.5 $MtCO_2$-eq yr^{-1} through the adoption of various mitigation practices. About 80% of the technical mitigation potential could be achieved by adopting cost-saving measures. Three mitigation options, i.e. efficient use of fertiliser, zero-tillage, and rice-water management, could deliver more than 50% of the total technical abatement potential. Under the BAU scenario the projected GHG emissions from major crop and livestock species is estimated at 489 $MtCO_2$-eq in 2030, whereas under mitigation scenario GHG emissions are estimated at 410 $MtCO_2$-eq implying a technical mitigation option of about 78.67 $MtCO_2$-eq yr^{-1} (Box 7.8, Figure 1). Major sources of projected emissions under the BAU scenario, in order of importance, were cattle, rice, buffalo, and small ruminants. Although livestock production and rice cultivation account for a major share of agricultural emissions, the highest mitigation potential was observed in rice (~36 $MtCO_2$-eq yr^{-1}) followed by buffalo (~ 14 $MtCO_2$-eq yr^{-1}), wheat (~11 $MtCO_2$-eq yr^{-1}) and cattle (~ 7 $MtCO_2$-eq yr^{-1}). Crops such as cotton and sugarcane each offered mitigation potential of about 5 $MtCO_2$-eq yr^{-1} while the mitigation potential from small ruminants (goat/sheep) was about 2 $MtCO_2$-eq yr^{-1}.

Sapkota et al. (2019) also estimated the magnitude of GHG savings per year through adoption of various mitigation measures, together with the total cost and net cost per unit of CO_2-eq abated. When the additional benefits of increased yield due to adoption of the mitigation measures were considered, about 80% of the technical mitigation potential (67.5 out of 85.5 $MtCO_2$-eq) could be achieved by cost-saving measures. When yield benefits were considered, green fodder supplements to ruminant diets was the most cost-effective mitigation measure, followed by vermicomposting and improved diet management of small ruminants. Mitigation measures such as fertigation and micro-irrigation, various methods of restoring degraded land and feed additives in livestock appear to be cost-prohibitive, even when considering yield benefits, if any. The study accounted for GHG emissions at the farm level and excluded emissions arising due to processing, marketing or consumption post farm-gate. It also did not include emissions from feed production, since livestock in India mostly rely on crop by-products and concentrates.



Box 7.8, Figure 1 Contribution of various crops and livestock species to total agricultural emission in 2012 (baseline) and by 2030 under business as usual (BAU) and mitigation scenarios for Indian Agricultural sector.

Source: Sapkota et al. (2019).

7.4.4 Bioenergy and BECCS

Activities, co-benefits, risks and implementation opportunities and barriers. Bioenergy is the use of biomass to produce energy carriers which can reduce GHGs by displacing the use of fossil fuels in the production of heat, electricity, and fuels (Box 7.9). Additionally, bioenergy combined with carbon capture and storage (BECCS) can provide Carbon Dioxide Removal (CDR) by durably storing (part of) the biogenic carbon in geological, terrestrial, or ocean reservoirs, or in products, further contributing to GHG emission reduction potential (Chapters 3, 4, 6 and 12) (Chum et al. 2011; Hammar and Levihn 2020; Emenike et al. 2020; Cabral et al. 2019: Wang et al. 2020: Johnsson et al. 2020).

Box 7.9 Bioenergy terminology and what is counted in estimates of mitigation potential

Bioenergy: energy derived from any form of biomass, including sewage sludge, municipal organic waste, by-flows in the agriculture and forestry sectors and energy crops.

Because bioenergy originates from a cycle of CO_2 it can reduce GHG emission by substituting fossil fuels in a range of applications.

Bioenergy systems can also provide carbon dioxide removal (CDR) when the biogenic CO_2 emitted from bioenergy use is captured and deposited in geological storages (bioenergy with carbon capture and storage, BECCS).

In the quantitative summation in this chapter (Table 7.4) only the CDR component of BECCS is considered. The substitution effects of bioenergy use are covered in the chapters covering Energy, Industry and Transport.

The BECCS contribution outlined in Tables 7.4 and 7.5 is based on studies that differ concerning inclusion of potential changes in the amount of carbon stored in soils and vegetation on the land that provided the biomass for BECCS. Increased land carbon storage enhances the mitigation and reduced land carbon storage diminishes the mitigation.

Several AFOLU mitigation options that provide mitigation through emissions reduction and/or carbon storage on land, can in addition produce bioenergy directly (biogas from manure management) or biomass (A/R, agroforestry), which provide opportunity for additional mitigation through substitution of fossil fuels and/or other products. Such additional mitigation is not included in the quantification of AFOLU mitigation potentials in Tables 7.4 and 7.5, nor included in the bioenergy resource potentials in Section 7.4.4.

Modern bioenergy systems (as opposed to traditional use of fuelwood and other low-quality cooking and heating fuels) currently provides approximately 30 EJ yr^{-1} of primary energy (IEA, 2019). These bioenergy systems (through with clear limits on maximum volumes) are commonly integrated components of forest and agriculture production systems and value chains that also produce food, feed, lumber, paper and other biobased products and can contribute to mitigation by displacing GHG-intensive products (Chapter 12). Bioenergy accounts for about 90% of renewable industrial heat consumption, mainly in industries that can use their own biomass waste and residues, such as the pulp and paper industry, food industry, and ethanol production plants (Chapters 6 and 11) (IEA 2020).

Bioenergy and BECCS can be associated with a range of co-benefits and adverse side-effects (Jia et al. 2019). But the integrated nature of bioenergy systems makes it difficult to disentangle bioenergy development from the overall development in the AFOLU sector. It is not possible to accurately determine the scale of bioenergy and BECCS deployment at which detrimental impacts outweigh the mitigation and other benefits, due to uncertainties in the consequences of bioenergy and BECCS at different scales (SRCCL, Cross-Chapter Box 7), and the amount of mitigation achieved (Box 7.10), which depend on inherently uncertain factors, such as future food demand, climate change, development in agriculture and forestry and associated food and forest industries, and future governance systems reflecting societal preferences and priorities concerning different sustainability criteria (Turner 2018b; Daioglou et al. 2019; Kalt et al. 2020, Wu et al. 2019) (Robledo-Abad et al. 2017) (Calvin et al, submitted).

It is indisputable that very large increases in the use of bioenergy and BECCS, as projected in many climate change mitigation scenarios originating from integrated assessment models, will put significant stresses on land use and ecosystems, and is subject to a range of sustainability concerns including competition for scarce land and freshwater, availability of phosphorous resources, land use change, and diminishing capacity of ecosystems to support biodiversity and essential ecosystem services (Smith et al. 2019; Popp et al. 2017; Heck et al. 2018; Hurlbert et al. 2019; Humpenöder et al. 2018; Rulli et al. 2016) (Brondizio et al., 2019; Hasegawa 2018; Hasegawa 2020; Fujimori 2019, Giffiths 2018, Dooley and Kartha, 2018, Drews et al. 2020, Schulze et al. 2020, Stenzel et al., 2020).

At the same time, literature (further described below) has also highlighted how the agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with supply of food, construction timber, and other biobased products, reducing the conversion pressure on natural ecosystems. Principal means include sustainable intensification of existing arable cropping systems to produce significantly more biomass, improvements in livestock productivity, forest management to increase wood production, changes to industrial processes to improve biomass conversion efficiencies and the use of residues and waste to produce fuels, electricity and heat. Changes in food consumption patterns towards less land demanding food can also help reduce the pressure on land resources (van Vuuren et al. 2018; Parodi et al. 2018; Springmann et al. 2018; Rosenzweig et al. 2020; Clark et al. 2020) (Section 7.4 and Chapter 12 Section 12.4).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Many of the more stringent mitigation scenarios in AR5 relied heavily on bioenergy and BECCS. The SR1.5 reported a range for the theoretical potential of BECCS (2100) at 1-85 $GtCO_2$-eq yr^{-1}, reduced to 0.5 to 5 $GtCO_2$-eq yr^{-1} when applying constraints reflecting sustainability concerns, at a cost of 100-200 USD tCO_2^{-1} (Fuss et al. 2018). The SRCCL reported a technical potential for BECCS at 0.4-11.3 $GtCO_2$ yr^{-1} (*medium confidence*), noting that most estimates do not include socio-economic barriers, the impacts of future climate change or non-GHG climate forcings (Shukla et al. 2019). The reported potentials include only the CDR component of BECCS, i.e., exclude mitigation achieved from substitution of fossil fuels. It also excludes emissions associated with land use practices, e.g., nitrogen fertiliser use, and effects of biomass production systems on land carbon. The SR1.5 and SRCCL highlighted that bioenergy and BECCS can be associated with co-benefits and adverse side-effects that are context specific.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). The role of BECCS as a dominant CDR measure in mitigation pathways has been reduced compared to earlier IAM results due to a larger variation of underlying assumptions about socio-economic drivers and associated energy and food demand, incorporation of a larger portfolio of mitigation and CDR options, and targeted analysis of deployment limits for specific CDR options, such as availability of land for energy and reforestation. Scenarios exploring the potentials of non-CO_2 emissions reduction and demand-side mitigation show reduced dependence on CDR and also reduced pressure on land (Grubler et al. 2018; Van Vuuren et al. 2018; Smith et al. 2020). The prevalence of bioenergy and BECCS in IAMs might become further reduced as additional land-based CDR options are built into IAMs.

Approaches to analyse the mitigation potential of bioenergy and BECCS rely on increasingly spatially explicit data supported by advances in the modelling of crop productivity and land use in agriculture and forestry, as well as land carbon stocks, hydrology, more subtle land management changes, and ecosystem properties (Wu et al, 2019, Li et al. 2020, Turner et al 2018b). These advances have enabled more comprehensive analyses of the multitude of factors that influence the contribution of bioenergy and BECCS in mitigation scenarios and also associated co-benefits and adverse side-effects. Yet, integrated assessment models do not capture subtle changes in land management and industrial/energy/transport systems yet, such as the use of integrated crop-livestock-forestry systems (Daioglou et al. 2019, Wu et al., 2019, Rose et al. 2021). Studies using other methods and models provide complementary information and insights.

Specifically, a growing body of literature investigates opportunities for strategic integration of biomass production systems (commonly perennial plants) into agricultural landscapes to provide biomass for energy and other biobased products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, increased soil carbon, pollination, pest and disease control, and flood regulation (Cross-Working Group Box 3 in Chapter 12). Similarly, climate-smart forestry puts forward a wide range of measures (see Box 7.3) adapted to regional circumstances in forest sectors, enabling co-benefits in nature conservation, soil protection, employment and income generation, and provision of renewable biomass for buildings, bioenergy and other biobased products.

Studies of land use approaches that combine biomass production with specific co-benefits commonly apply a restricted geographical scope and have not been systematically recapitulated to obtain global estimates of biomass supply potentials. One exception is the significant literature available concerning the use of marginal and degraded lands, as well as the use of integrated production systems, which can reduce land use pressure associated with bioenergy expansion, help restore the productive and adaptive capacity, and increase the ecological and market value of these lands (Elbersen et al. 2019, Awasthi et al. 2017, Chiaramonti and Panoutsou, 2018, Fernando et al. 2018, Rahman et al. 2019, Fritsche et al 2017). In the SRCCL, the presented range for available degraded or abandoned land was 32 - 1400 Mha (Jia et al. 2019). Recent regional assessments not included in the SRCCL found up to 69 Mha in EU-28, 185 Mha in China, 9.5 Mha in Canada, and 127 Mha in the United States (Elbersen et al. 2019, Zhang et al 2020, Emery et al. 2017, Liu et al. 2017). However, as with Jia et al. (2019), these estimates are very sensitive to sustainability criteria, land class definitions, land mapping methods, and environmental and economic considerations of marginal land and other environmental and technical constraints (Xue et al. 2016; Emery et al. 2017).

Recent estimates of technical biomass potentials fall within previous ranges corresponding to *medium agreement*. Example studies include (Turner 2018b; Daioglou et al. 2019; Kalt et al. 2020, Wu et al. 2019) that adopt constraints to minimise interference with food production, biodiversity and other environmental constraints, arriving at a technical potential for dedicated lignocellulosic crops at approximately 70 EJ yr^{-1} today and 46-245 EJ yr^{-1} in 2050 with a land requirement of 400-500 Mha. Studies of residue potentials include (Hansen et al 2019; Kalt et al. 2020) that estimate residue availability based on projections of agricultural and forestry activity: 4-57 EJ yr^{-1} by 2050, increasing to 50-90 EJ yr^{-1} by 2100.

Box 7.10 Climate change mitigation value of bioenergy and BECCS: how to calculate

The net GHG effects of using bioenergy depend on: (i) how much GHG emissions are avoided when the bioenergy is used instead of another energy source; and (ii) how the associated land use (and possibly LUC) influences the amount of carbon that is stored in vegetation and soils over time. Bioenergy and associated land use also influence the climate through (i) particulate and black carbon emissions from small-scale bioenergy use; (ii) aerosol emissions associated with forests; and (iii) modifying physical properties of the surface, altering for instance evapotranspiration and albedo.

Studies arrive at varying conclusions about the mitigation value of bioenergy and BECCS due to the large diversity of bioenergy systems, and varying context conditions where they are deployed (Elshout 2015; Harper et al 2018; Kalt et al 2019; Fajardy 2017; Muri 2018; Brandão et al. 2019; Buchspeis et al. 2020). Important factors include type of feedstock, land management practice, energy conversion efficiency, whether CCS is used, type of bioenergy product (and possible co-products) and emissions intensity of the products being displaced, the geographic location, and the land use/cover prior to bioenergy deployment (Fearnside 2000; Fearnside et al. 2009; Rokityanskiy et al. 2007; Erb et al. 2012; Searchinger et al. 2017; Cherubini et al. 2009; Zhu et al. 2017; Hanssen et al. 2020; Daioglou et al. 2015; Staples et al. 2017).

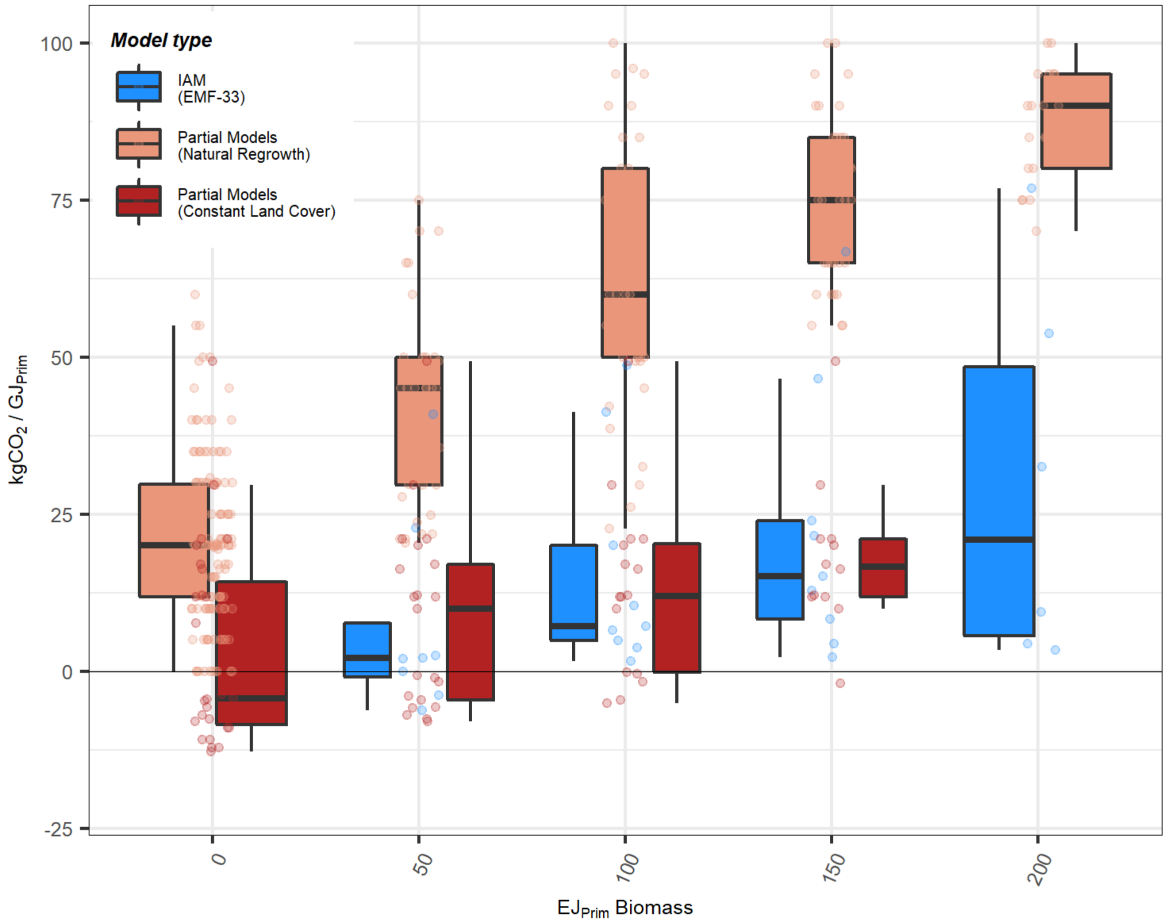
Studies also arrive at contrasting conclusion when very similar bioenergy systems and context conditions are evaluated, due to that different methodologies and assumptions about critical parameters are used in the analyses (Muri 2018; Fajardy 2017; Prisley et al. 2018; Sterman et al. 2018a; 201b; Harper et al 2018; Kalt et al 2019; Brandão et al. 2019; Albers et al. 2019; Buchspeis et al. 2020; Bessou et al. 2020; Rolls and Forster 2020). Approaches to define spatial and temporal system boundaries, and counterfactual land use have an important influence on the quantification of climate change effects of bioenergy, especially related to how bioenergy-driven land use and LUC influence land carbon balances (Elshout et al. 2015; Cintas et al. 2016; Daioglou et al. 2017; Bentsen 2017; Koponen et al. 2018; Peñaloza et al. 2019; Hanssen et al. 2020). Studies have shown that land carbon losses due to land use and LUC can delay the achievement of net GHG savings. This delay can range from a few years to many decades or even more than a century if high carbon land (e.g., dense forests and peatland) would be converted to energy crop (Bamiére and Ballassen 2018; Elshout et al. 2019; Abraha et al. 2019). A recent study by Hanssen et al (2020) showed that the impact of LUC with resulting land carbon losses on the net GHG savings critically depends on the fate of pre-conversion biomass (e.g., burned on site or used in products) and whether bioenergy is combined with CCS to achieve CDR.Thus, the effectiveness of bioenergy at mitigating GHG emissions varies a lot across resources, production locations, land legacy effects, bioenergy production methods, lifecycle emissions, and the use of BECCS

Box 7.10 Figure 1 shows emission-supply curves in 2050 (kgCO_2-eq GJ^{-1}) for biomass supply consisting of residues and crops grown on cropland not needed for food. One curve is determined from stylised scenarios using integrated assessment models (IAMs). Two curves are determined form partial models (see info in Box 7.10 Figure 1 caption). In the "*Constant Land Cover*" case, the emission-supply curve reflects supply chain emissions and changes in land carbon storage caused by the biomass supply system. This curve aligns relatively well with the curve determined with IAMs. In the "*Natural Regrowth*" case, extra emissions are added on top of the emissions included in the "*Constant Land Cover*" case. These extra emissions correspond to the carbon sequestration that would have taken place in a counterfactual scenario where the surplus cropland and natural lands is instead subject to (continued) natural vegetation regrowth.

This modified emission-supply curve gives an indication of the diminishing marginal net GHG savings achieved when the biomass is used instead of an alternative primary energy source, in a scenario where the surplus cropland and natural lands not used for energy crops is subject to (continued) natural vegetation regrowth. To illustrate, if the biomass and the alternative primary energy source can be converted into final energy carriers with the same efficiency, and if the emissions factor for the alternative primary energy source is 75 kg CO_2 GJ^{-1}, then the median value in the "*Natural Regrowth*" emission-supply curve in Box 7.10 Figure 1, indicates that up to about 150 EJ of biomass can be produced and used for energy while achieving net GHG savings.

The emission factors for natural gas and coal are around 56 and 95 kg CO_2 GJ^{-1}. To enable comparison as above these emission factors must be adjusted based on information about conversion efficiencies for biomass, coal and natural gas plants producing energy carriers of interest.

Not shown in Box 7.10 Figure 1; the emission-supply curves would be adjusted downwards if bioenergy is combined with CCS to provide CDR, or if land management can improve land carbon balances.



Box 7.10, Figure 1 Emission-supply curves for primary biomass supply by 2050 (residues and crops grown on cropland not needed for food), as determined from partial models (Daioglou et al. 2017; Kalt et al. 2020), and stylised scenarios from the EMF-33 project using Integrated Assessment Models (Rose et al. 2021). All methods include LUC (direct and indirect) emissions. For the Partial models, results include counterfactual carbon fluxes (see text). The partial models include a more detailed representation of the emissions, including Life-Cycle emissions from fertiliser production. IAM models may include economic feedbacks such as intensification as a result of increasing prices. As an indication: for natural gas the emission factor is around 56, for coal around 95 kg CO_2 GJ^{-1}.

Critical assessment and conclusion. Based on studies to date, the technical net CDR potential of BECCS by 2050 is 0.5-11.3 $GtCO_2$ yr^{-1} (median = 5 $GtCO_2$ yr^{-1}) globally, of which 0.5-3.5 $GtCO_2$ yr^{-1} (1.6 $GtCO_2$ yr^{-1}) is available at below USD 100/tCO_2 (*medium confidence*). The equivalent economic potential as derived from IAMs is 0-2.8 $GtCO_2$ yr^{-1} (0.58 $GtCO_2$ yr^{-1}) (Table 7.5). The technical potential for dedicated lignocellulosic crops is in recent example studies estimated at approximately 70 EJ yr^{-1} today and 46-245 EJ yr^{-1} in 2050. While for agricultural and forestry residues it is estimated 4-57 EJ yr^{-1} may be available by 2050.

The implications of bioenergy and BECCS deployment for mitigation and other sustainability criteria are context dependent and influenced by feedstock, management regime, climate, scale of deployment and the counterfactual land use and energy system (Daioglou et al. 2015; Elshout et al. 2015; Daioglou et al. 2017; Staples et al. 2017; Carvalho et al. 2017; Mouratiadou et al. 2020; Buchspies et al. 2020; Hanssen et al. 2020). Limitations of the existing models, and uncertainty over the future context with respect to the many variables that influence availability of biomass and land resources, prevent precise quantification of the sustainability implications for different scales of bioenergy implementation.

Poorly deployed bioenergy and BECCS options that displace other land uses, such as widespread planting of monoculture bioenergy plantations, can cause negative outcomes for food security and a range of other sustainability criteria. Expansion at the expense of areas with high carbon stock could undo climate benefits of bioenergy and BECCS (Rochedo et al. 2018; Daioglou et al. 2020a; Juninger et al. 2019; Ollson et al. 2016; Otto et al. 2015; Galik et al. 2020; Searchinger 2017; Vaughan et al. 2018). But if carefully deployed, as part of a broader AFOLU mitigation portfolio, bioenergy systems can enable synergistic interconnections between land uses and support a range of SDGs. The use of organic waste and residues can support significant volumes of bioenergy and BECCS with relatively lower land-use change risks than dedicated biomass production systems (*medium evidence, high agreement*).

Risks for possible negative consequences of bioenergy and BECCS can be reduced by designing and deploying strategies that encourage (i) land management that protects carbon stocks and environmental functions while increasing land productivity and closing yield gaps (van Ittersum et al. 2013, Gerssen-Gondelach et al. 2015); (ii) supply chains and final consumption that are well managed and deployed at appropriate levels (Donnison et al. 2020; Fajardy et al. 2018); and (iii) development of a common agenda for energy, agriculture, forestry, and traditional bio-based products, coordinated at national and multinational levels via sustainability criteria as e.g. a global circular bioeconomy alliance https://efi.int/cba (*very high confidence*).

Finally, the technical feasibility of BECCS depends on the roll-out of CCS technologies. The required technological improvements call for R&D investments in advanced bioenergy technologies (liquid fuels, gasification, bio-hydrogen) based on lignocellulosic feedstocks as well as their combination with carbon capture and storage (Daioglou et al. 2020b, Baker et al 2015).

7.4.5 Demand-side measures

7.4.5.1 Shift to sustainable healthy diets

Activities, co-benefits, risks and implementation opportunities and barriers. The term 'Sustainable healthy diets' refers to dietary patterns that 'promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable' (FAO and WHO 2019). In addition to climate mitigation gains, a transition towards more plant-based consumption and reduced consumption of animal-based foods could reduce pressure on forests and land used for feed, support the preservation of biodiversity and planetary health (FAO 2018), and contribute to preventing forms of malnutrition (i.e. undernutrition, micronutrient deficiency, overweight and obesity) in developing countries (Chapter 12, Section 12.4.). Other co-benefits include lowering the risk of cardiovascular disease, type 2 diabetes and obesity, and reducing mortality from diet-related non-communicable diseases (Toumpanakis et al. 2018; Satija and Hu 2018; Faber et al. 2020; Magkos et al. 2020). However, transition towards sustainable healthy diets might drive habitat and biodiversity loss (particularly in the Atlantic Forest, Cerrado and Brazilian Amazon), and could have adverse impacts on the economic stability of the agricultural sector (Macdiarmid 2013; Aschemann-Witzel 2015; Van Loo et al. 2017). Therefore, shifting toward sustainable and healthy diets requires effective food-system oriented reform policies that integrate agriculture, health and environment policies to comprehensively address synergies and conflicts in co-lateral sectors (agriculture, trade, health, environment protection etc.) and capture spill-over effects on other inter-connected challenges in food systems (climate change, biodiversity loss, food poverty) (FAO and WHO 2019; Galli et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. According to the AR5, changes in human diets and consumption patterns can substantially reduce emissions from diverted agricultural production and avoided land-use change (Smith et al. 2014), with a total mitigation potential ranging from 5.3 to 20.2 $GtCO_2$-eq yr^{-1} by 2050. In particular, the substitution of animal-source food with plant-based food while maintaining adequate protein content both quantitatively and qualitatively together with the reduction of overconsumption in regions with high consumption of animal-source foods can have a significant impact on GHG emissions from the food production lifecycle. In the SRCCL, a "contract and converge" model of transition to sustainable healthy diets was suggested as an effective approach to promote adaptation to climate change through food demand, by reducing food consumption in over-consuming populations and increasing consumption of some food groups in populations where minimum nutritional needs are not met (Smith et al. 2019). The total technical mitigation potential of changes in human diets and consumption patterns was estimated as 0.7 - 8 $GtCO_2$-eq yr^{-1} by 2050 (SRCCL, Chapter 2; Springmann et al. 2016; Hawken 2017; Tilman and Clark 2014), which could be achieved through promoting the adoption of balanced diets, and featuring plant-based foods (veganism, vegetarianism), low ruminant meat consumption and the production of animal-source food in resilient, sustainable and low-GHG emission food systems.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, several additional studies have examined the mitigation potential of shifting towards sustainable and healthy diets on a global and regional level. Global studies continue to emphasise that reducing the demand for animal-source foods and increasing proportions of plant-rich foods in diets present high potential for climate change mitigation. Springmann et al. (2018) estimated that dietary changes toward diets in line with global dietary guidelines for the consumption of red meat, sugar, fruits and vegetables, and total energy intake could reduce GHG emissions by 29% and other environmental impacts by 5–9% compared with the baseline projection for 2050. More so, shifting towards more plant-based diets that include lower amounts of red and other meats and greater amounts of fruits, vegetables, nuts and legumes could reduce GHG emissions by 56% and other environmental impacts by 6–22% compared with the baseline projection for 2050. Poore and Nemecek (2019) revealed that shifting towards diets that exclude animal-source food could reduce land use by 3.1 billion ha, decrease food-related GHG emissions by 6.6 $GtCO_2$-eq yr^{-1}, acidification by 50%, eutrophication by 49%, and scarcity-weighted freshwater withdrawals by 19% for a 2010 reference year. These estimates are based on producing new vegetable proteins with impacts between the 10^{th} and 90^{th}-percentile impacts of existing production. Frank et al. (2019) found that shifting to healthier diets would allow for a more balanced per capita meat consumption across regions for the same level of mitigation reduction compared to mitigation pathways with more standardised mitigation policy assumptions. Ivanova et al. (2020) systematically reviewed the literature since 2011 regarding the mitigation potential of consumption options and revealed that a dietary change toward lower amounts of animal products consumed can be associated with mitigation potentials of 0.4-2.1 tCO_2-eq $capita^{-1}$ for a vegan diet, of 0.01-1.5 for a vegetarian diet, and of 0.1-2.0 for Mediterranean and similar diet.

Regionally, data in Table 7.5. show that shifting towards sustainable healthy diets could have technical mitigation potential varying cross regions from 0.12 $GtCO_2$ yr^{-1} in Eastern Europe and West-Central Asia to 0.96 in Asia and developing Pacific, for the period 2020-2050, with equivalent economic potentials ranging from 0.07 to 0.6 $GtCO_2$ yr^{-1} (Table 7.5). In the EU, Latka et al. (in press) found that moving to healthy diets could bring about annual reductions of non-CO_2 emissions from agriculture of 12-111 $MtCO_2$-eq yr^{-1}. However, to achieve the conversion to healthy diets through price incentives only considerable tax levels would be required. At the country level, Drew et al. (2020) showed that a transition towards a healthier, more climate-friendly food system in New Zealand and shifting to a plant-based diet would be substantially less climate-polluting (1.2-1.8 kg CO_2 kg^{-1}) than animal-based diets (12–21 $kgCO_2$-eq kg^{-1}). In addition, aligning household consumption with the New Zealand dietary guidelines (NDG) would confer diet-related emissions savings of 4–42%, depending on the degree of dietary change and food waste minimisation pursued, and would also confer large health gains (1.0–1.5 million quality-adjusted life-years) and health care system cost savings (NZ$14–20 billion). Arrieta and González (2018) analysed the potential climate change mitigation through dietary changes in Argentina, a country with high beef consumption, under four dietary scenarios following the nutritional recommendations of the NDG. They found that if the NDG, which suggests a 50% reduction of total daily intake of meats compared to current consumption, if adopted, a reduction of 28%, to 3.95 ± 0.96 in GHG emissions appear possible while maintaining a healthy and balanced diet. Esteve-Llorens et al. (2020) reported that an adoption of a more sustainable dietary pattern in Portugal can lower the carbon footprint by approximately 25% to approach the values of recommended diets for the Mediterranean and the Atlantic regions and increase the nutritional quality of around 67%. Batlle-Bayer et al. (2020) showed that the adoption of the NDG-based diet in Spain, which recommends larger consumption of plant-based products and reduced red meat and sugary product intake, can potentially reduce GHG emissions, land use and blue water footprint by between 15 and 60% of current eating patterns. In contrast to the previous cited studies, Aleksandrowicz et al. (2019) estimated that meeting healthy dietary guidelines in India slightly increased environmental footprints by about 3–5% across GHG emissions, blue and green water footprints and land use. However, their results revealed that national averages mask substantial variation within the six major Indian sub-regions. Specifically, shifting to healthy diets, among population groups with dietary energy intake below the recommended guidelines, was found to potentially increase GHG emissions, blue water footprints, green water footprints, and land use by 28%, 18, 34%, and 41%, respectively. Decreased environmental impacts were seen among those who currently consume above recommended dietary energy (−6 to −16% across footprints). In addition, the adoption of affluent diets by the whole Indian population was found to be associated with an increase of 19–36% across the environmental indicators.

Critical assessment and conclusion. Shifting to sustainable healthy diets has significant potential to achieve global GHG mitigation targets as well as public health and environmental benefits (*high confidence*). Specifically, based on studies to date, shifting toward sustainable healthy diets has a technical potential ranging from 0.5 to 9.4 $GtCO_2$-eq yr^{-1} (median = 4.3) based on a range of GWP_{100} values for CH_4 and N_2O. A shift to more sustainable and healthy diets is generally feasible in many regions (*medium confidence*). However, potential varies across regions as diets are location- and community- specific, and thus may be influenced by local production practices, technical and financial barriers and associated livelihoods, everyday life and behavioural and cultural norms around food consumption (Meybeck and Gitz 2017; FAO 2018; Creutzig et al. 2018). Therefore, a transition towards low-GHG emission diets and achieving their mitigation potential requires a combination of appropriate policies, financial and non-financial incentives and awareness-raising campaigns to induce changes in consumer behaviour with potential synergies between climate objectives, health and equity (Rust et al. 2020).

7.4.5.2 Reduce food loss and waste

Activities, co-benefits, risks and implementation opportunities and barriers. Food loss and waste (FLW) refer to the edible parts of plants and animals produced for human consumption that are not ultimately consumed. Food loss occurs through spoilage, spilling or other unintended consequences due to limitations in agricultural infrastructure, storage and packaging (Parfitt et al. 2010). Food waste typically takes place at the distribution (retail and food service) and consumption stages in the food supply chain and refers to food appropriate for human consumption that is discarded or left to spoil (HLPE 2014). Options that could reduce FLW include: investing in harvesting and post-harvesting technologies in the developing countries, taxing and other incentives to reduce retail and consumer-level waste in developed countries, providing options of longer-lasting products and other behavioural changes (e.g. through information provision) that cause dietary and consumption changes and motivate consumers to actively make decisions that reduce FLW. The interlinkages between reducing FLW and food system sustainability are discussed in Chapter 12.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In AR5, reduced FLW was considered as a mitigation measure that could substantially lower emissions. It was suggested that FLW reductions in the food supply chain could reduce GHG emissions by 0.6–6.0 $GtCO_2$-eq yr^{-1} (Smith et al. 2014). The mitigation potential of reducing food and agricultural waste was estimated in the SRCCL at 0.76-4.5 $GtCO_2$-eq yr^{-1} (SRCCL, Chapter 2: Bajželj et al. 2014; Dickie et al. 2014; Hawken 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, there have been very few quantitative estimates of the mitigation potential of FLW reductions and these are highly uncertain. Generally, evidence suggests that reducing FLW together with overall food intake could have substantial mitigation potential, equating to an average of 0.3 tCO_2-eq $capita^{-1}$ (Ivanova et al. 2020). Some regional sectoral studies indicate that reducing FLW in the EU can reduce emissions by 186 $MtCO_2$-eq yr^{-1}, the equivalent of around 15% of the environmental impacts (climate, acidification, and eutrophication) of the entire food value chain (Scherhaufer et al. 2018). In the UK, disruptive low-carbon innovations relating to FLW reduction were found to be associated with potential emissions reductions ranging between 2.6 and 3.6 $MtCO_2$-eq (Wilson et al. 2018). Other studies investigated the effect of tax mechanisms, such as 'pay as you throw' for household waste, on the mitigation potential of reducing FLW. Generally, these mechanisms are recognised as particularly effective in reducing the amount of waste and increasing the recycling rate of households (Carattini et al. 2018; Rogissart et al. 2019). Technological FWL mitigation opportunities exist throughout the food supply chain; post-harvest opportunities for FLW reductions are discussed in Chapter 12. In the present assessment, we estimate greatest economic (at USD 100/tCO_2) mitigation potential for the period 2020-2050 from FLW reduction to be in Asia and the developing Pacific (0.2 $GtCO_2$-eq yr^{-1}), with most other regions showing similar potential (0.1 $GtCO_2$-eq yr^{-1}) (Table 7.5).

Recent literature identifies a range of barriers to climate change mitigation through FLW reduction, which are linked to technological, biophysical, socio-economic, financial and cultural contexts at regional and local levels (Blok et al. 2020; Vogel and Meyer 2018; Gromko and Abdurasulova 2019; Rogissart et al. 2019). Examples of these barriers include infrastructural and capacity limitations, institutional regulations, financial resources, constraining resources (e.g. energy), information gaps (e.g. with retailers), and consumers' behaviour (Blok et al. 2020; Gromko and Abdurasulova 2019). However, reductions of FLW along the food chain have not only a mitigation potential but could also bring a range of benefits for reducing environmental stress (e.g. water and land competition, land degradation, desertification), safeguarding food security and reducing poverty (Galford et al. 2020; Venkatramanan et al. 2019). Additionally, FLW reduction is crucial for achieving SDG 12 which calls for ensuring 'sustainable consumption and production patterns' through lowering per capita global food waste by 50% at the retail and consumer level and reducing food losses along food supply chains by 2030. In this respect, it is estimated that reducing FLW can free up several million km^2 of land (*high confidence*).

Critical assessment and conclusion. In conclusion, there is *medium confidence* that reduced FLW has a global technical mitigation potential, using GWP_{100} and a range of IPCC values for CH_4 and N_2O of 0.9-5.8 $GtCO_2$-eq yr^{-1} (median = 2.1). Regionally, FLW reduction is feasible anywhere but its potential needs to be understood in a wider and changing socio-cultural context that determines nutrition (*high confidence*).

7.4.5.3 Enhanced use of wood products

Activities, co-benefits, risks and implementation opportunities and barriers. The use of wood products refers to the fate of harvested wood for material uses and includes two distinctly different components that affect the carbon cycle. The first component includes the storage of carbon in wood products, while the second refers to material substitution. When harvested wood is used for the manufacture of wood products, carbon remains stored in these products depending on their end use and lifetime. Carbon storage in wood products can be increased through either enhancing the inflow of products in use, or effectively reducing the outflow of the products after use. This can be achieved through additional harvest (Johnston and Radeloff 2019; Pilli et al. 2015), changing the allocation of harvested wood to long-lived wood products increasing products' lifetime and increasing recycling (Brunet et al. 2017; Jasinevičius et al. 2017; Xu et al. 2018). Material substitution involves the use of wood for building, textiles, or other applications instead of other materials (e.g. concrete, steel) to avoid or reduce emissions associated with the production, use and disposal of the products.

The benefits and risks of enhanced use of wood products are closely linked to forest management. First of all, the enhanced use of wood products could potentially activate or lead to improved sustainable forest management that can mitigate and adapt to climate change, considering ecosystem services and biodiversity (Verkerk et al. 2020). Secondly, carbon storage in wood products and the potential for substitution effects can be increased by additional harvest, but that would decrease carbon storage in forest biomass in the short term (Smith et al. 2019). Conversely, reduced harvest may lead to gains in carbon storage in forest ecosystems locally, but these gains may be offset through international trade of forest products causing increased harvesting pressure or even degradation elsewhere (Kastner et al. 2011; Kallio and Solberg 2018; Pendrill et al. 2019a; 2019b). Thirdly, there are environmental risks linked to wood production in case of poor forest management (e.g. biodiversity; Chaudhary et al. 2016). There are also environmental impacts (e.g. eutrophication, acidification, toxicity) associated with the processing, manufacturing, use and disposal of wood products (Klein et al. 2015; Mäkelä 2017; Adhikari and Ozarska 2018; Baumgartner 2019), although the understanding of these impacts is still limited and these impacts need to be compared with the impacts that occur during the manufacturing, use and disposal of the non-wood products they displace (Weiss et al. 2012; Churkina et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. There is strong evidence at the product level that wood products are associated with less greenhouse emissions in their production, use and disposal over their life-time compared to products made from emission-intensive and non-renewable materials (Sathre and O'Connor 2010; Geng et al. 2017; Leskinen et al. 2018). However, there is still limited understanding of the substitution effects at the level of markets, countries, or global regions, presumably due to limited information on end uses of wood and the difficulty to determine which materials that are substituted (Leskinen et al. 2018). AR5 did not report on the mitigation potential of wood products. The SRCCL (Chapters 2 and 6) finds that some studies indicate significant mitigation potentials for material substitution, but concludes that the global, technical mitigation potential for material substitution for construction applications ranges from 0.25-1 $GtCO_2$-eq yr^{-1} (*medium confidence*) (McLaren 2012; Miner 2010; Roe et al. 2019), which excludes the mitigation potential of carbon storage in wood products. In general, the SRCCL (Chapter 4, Section 4.8) considers that greater mitigation benefits are achieved if harvested wood products are used for products with long carbon retention time and high substitution (or displacement) factors (Olssen et al. 2019). Despite this potential, enhanced use of wood products is currently not considered in integrated assessment models used for mitigation pathways.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, additional studies examined the mitigation potential of the enhanced use of wood products (Table 7.5). A global forest sector modelling study (Johnston and Radeloff 2019) estimated that carbon storage in wood products represented a net sink of 0.34 $GtCO_2$-eq yr^{-1} globally in 2015 and which could provide an average mitigation potential of 0.33-0.41 $GtCO_2$-eq yr^{-1} for the period 2020-2050, based on the future socio-economic development (SSP scenarios) and its effect on the production and consumption of wood products. Traded feedstock provided another 0.071 $GtCO_2$ yr^{-1} of carbon storage in 2015 and 0.12 $GtCO_2$ yr^{-1} by 2065. These potentials exclude the effect of material substitution. At a regional level, the study estimated the mitigation potential at 5 $MtCO_2$-eq yr^{-1} for Africa and the Middle East, 162 $MtCO_2$-eq yr^{-1} for Asia and developing Pacific, 90 $MtCO_2$-eq yr^{-1} for Developed Countries, 12 $MtCO_2$-eq yr^{-1} Eastern Europe and West-Central Asia and 22 $MtCO_2$-eq yr^{-1} for Latin America and the Caribbean by 2065 (Johnston and Radeloff 2019). Another recent study estimated the global mitigation potential of mid-rise urban buildings designed with engineered wood products at 0.04-3.7 $GtCO_2$ yr^{-1} (Churkina et al. 2020). The range in these estimates depends on the amount of wood used in construction and how fast countries adopt new building practices, as well as the floor space per capita. This technical mitigation potential considers carbon storage (0.03-2.5 ($GtCO_2$ yr^{-1}) and material substitution (0.0-1.2 $GtCO_2$ yr^{-1}). The upper bound of the estimated potential requires large amounts of roundwood obtained from additional harvest or redirecting roundwood from use as a fuel to long-lived construction products. However, the material substitution potential may be considered a conservative estimate as it does not consider the mitigation potential of reuse, recycling or energy production at the end-of-life. Another study (Oliver et al. 2014) estimated that using wood to substitute for concrete and steel as building materials could provide a technical mitigation potential of 0.78-1.73 $GtCO_2$ yr^{-1} achieved through carbon storage in wood products and through material and energy substitution.

A larger body of literature exists on the mitigation potential of the enhanced use of wood products for countries or global regions. Notably for Europe, there are a significant number of studies that estimate mitigation through carbon storage in wood products (Amiri et al. 2020; Pilli et al. 2015; Pilli et al. 2017; Brunet Navarro et al. 2017; Paluš et al. 2020), material substitution (Soimakallio et al. 2016), or both (Eriksson et al. 2012; Rüter et al. 2016; Braun et al. 2016; Lundmark et al. 2014; Werner et al. 2005; Werner et al. 2010; Jasinevičius et al. 2017; Heinonen et al. 2017; Hurmekoski et al. 2020; Parobek et al. 2019; Nabuurs et al. 2017; Nabuurs et al. 2018), mostly at the national level. For Europe, the recent (historical) wood product sink has been estimated at 0.04-0.05 $GtCO_2$- yr^{-1} (approximately 10% of the forest carbon sink) (Pilli et al. 2015; Brunet Navarro et al. 2017) and the future technical mitigation potential of carbon storage in wood products ranges from 0.01-0.068 $GtCO_2$ yr^{-1} by 2030 or 2040, depending on harvest level, the end use of the wood, the products' lifetime and recycling rate (Amiri et al. 2020; Pilli et al. 2015; Brunet Navarro et al. 2017). For other world regions, considerably fewer potential estimates exist. The existing estimates are mainly available for individual countries including China (Geng et al 2019a; 2019b), Japan (Kayo et al. 2014; Kayo and Noda 2018; Matsumoto et al. 2016, Canada (Chen et al. 2018; Smyth et al. 2014; Smyth et al. 2017; Smyth et al. 2018; Smyth et al. 2020; Xu et al. 2020) and the United States (Nepal et al. 2016; Tian et al. 2018).

The limited availability or absence of estimates of the future mitigation potential of enhanced use of wood products for many world regions represents an important knowledge gap, especially with regards to material substitution effects. Existing life cycle analysis studies on wood products mostly focus on (northern) Europe and North America, followed by Asia, while few or no studies exist for other world regions (Sahoo et al. 2019; Leskinen et al. 2018). Developing such estimates is hampered by limited information on end uses of wood, the difficulty to determine which non-wood materials that are substituted, as well as the future product design, efficiency, technology and energy supply of both the wood and non-wood products (Leskinen et al. 2018; Harmon 2019). Differences in data, methods and assumptions are important reasons for the large variability of carbon impacts of material substitution (Sathre and O'Connor 2011; Pomponi and Moncaster 2018). Finally, when wood is harvested, this affects the carbon stored in forest biomass and soils. The mitigation potential of enhanced use of wood products therefore needs to be considered together with the carbon balances of forest ecosystems (Harmon 2019; Seppälä et al. 2019; Soimakallio et al. 2016; Smyth et al. 201x)

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that the enhanced use of wood products through carbon storage and material substitution has a technical potential to contribute to climate change mitigation of 0.04-3.7 $GtCO_2$ yr^{-1} (median = 0.4). There is *strong evidence* and *high agreement* at the product level that material substitution provides benefits for climate change mitigation as wood products are associated with less greenhouse emissions over their lifetime compared to products made from emission-intensive and non-renewable materials. However, the evidence at the level of markets or countries is fairly limited for many parts of the world. There is *medium confidence* that material substitution and carbon storage in wood products contribute to climate change mitigation when also the carbon balances of forest ecosystems are considered. The total future mitigation potential will depend on the forest system considered, the type of wood products that are produced and substituted and the assumed production technologies and conversion efficiencies of these products.

7.5 AFOLU Integrated Models and Scenarios

This section assesses the literature and data available on potential future GHG dynamics in the AFOLU sector, the cost-effectiveness of different mitigation measures, and consequences of climate change mitigation pathways on land-use dynamics as well as relevant sustainable development indicators at the regional and global level.

Land-based mitigation options interact and create various trade-offs, and thus need to be assessed together as well as with mitigation options in other sectors, and in combination with other sustainability goals (Popp et al. 2014; Obersteiner et al. 2016; Roe et al 2019; van Vuuren et al. 2019; Frank et al. in press). The assessments of individual mitigation measures or sectoral estimates used to estimate mitigation potential in Section 7.4, when aggregated together, do not account for interactions and trade-offs. Integrative land-use models (ILMs) combine different land-based mitigation options and are partially included in Integrated Assessment Models (IAMs) which combine insights from various disciplines in a single framework and cover the largest sources of anthropogenic GHG emissions from different sectors. Over time, ILMs and IAMs have extended their system coverage (Johnson et al. 2019). However, the explicit modelling and analysis of integrated land-use systems is relatively new compared to other sectoral assessments such as the energy system (Jia et al. 2019). Consequently, ILMs as well as IAMs differ in their portfolio and representation of land-based mitigation options, the representation of sustainability goals other than climate action as well as the interplay with mitigation in other sectors (Johnson et al. 2019; van Soest et al. 2019). These structural differences have implications for the regional and global deployment of different mitigation options as well as their sustainability impacts.

As a consequence of the relative novelty of land-based mitigation assessment in ILMs and IAMs, the portfolio of land-based mitigation options does not cover the full option space as outlined in Section 7.4. The inclusion and detail of a specific mitigation measure differs across models. The representation of mitigation measures is influenced, on the one hand, by the availability of data for its techno-economic characteristics and future prospects as well as the computational challenge, e.g. in terms of spatial and process detail, to represent the measure, and on the other hand, by structural differences and general focus of the different ILMs, and prioritisation of different mitigation options by the modelling teams. Terrestrial Carbon Dioxide Removal (tCDR) options are only partially included in ILM and IAM analyses, which mostly rely on afforestation/reforestation and bioenergy with CCS (BECCS). Most ILM and IAM scenarios are based on the Shared Socio-economic Pathways (SSPs) (Riahi et al 2017), which is a set of contrasting future scenarios widely used in the research community such as in the CMIP6 exercise, the SRCCL and the IPBES global assessment. However, the coverage of land-based mitigation options in these scenarios is mostly limited to dietary changes, higher efficiency in food processing (especially in livestock production systems), reduction of food waste, increasing agricultural productivity, methane reductions in rice paddies, livestock and grazing management for reduced methane emissions from enteric fermentation, manure management, improvement of N-efficiency, international trade, first generation of biofuels, avoided deforestation, afforestation, bioenergy and BECCS (Popp et al. 2017; van Meijl et al. 2018; Frank et al 2019). Hence, there are mitigation options not being broadly included in integrated pathway modelling, especially nature based solutions (Griscom et al 2017; Roe et al 2019) such as soil carbon management, agroforestry or wetland management (Humpenöder et al. 2020) which have the potential to alter the contribution of land-based mitigation in terms of timing, potential and sustainability consequences (Frank et al. 2017). Furthermore, those types of models often lack a representation of emerging technologies ranging from biochar through nitrification inhibitors to methane inhibitors (Herrero et al. 2020). In contrast, to the SRCCL as well as Chapter 3 in this report, this sub-section assesses new items: future GHG dynamics in the AFOLU sector, the contribution of the AFOLU sector to climate change mitigation pathways, the estimated economic potential of AFOLU mitigation according to integrated assessments, and the consequences on land-use dynamics as well as relevant sustainable development indicators not only for the global dimension but also at the level of the IPCC five world regions.. In addition, this section investigates the relevance and value of single mitigation options in the interplay with underlying drivers as well as with other mitigation options.

In addition to a general evaluation of the scenarios available to this assessment (Ref to AR6 database), a set of possible mitigation pathways has been identified which are illustrative of a range of possibilities in their GHG and land-use impacts (especially related to their use of terrestrial CDR such as bioenergy) as well as their consequences for sustainable development at both the global as well as the regional level. They vary due to underlying socio-economic and policy assumptions, mitigation options considered, the level of inclusion of other sustainability goals (such as land and water restrictions for biodiversity conservation or food production), and models by which they are generated.

7.5.1 Regional GHG emissions and land dynamics

In most of the assessed mitigation pathways, the land sector is of great importance for climate change mitigation as it (i) turns from a source into a sink of atmospheric CO_2 due to large-scale afforestation and reforestation, (ii) provides high amounts of biomass for bioenergy or BECCS and (iii), even under improved agricultural management, still causes residual non-CO_2 emissions from agricultural production and (iv) interplays with sustainability dimensions other than climate action (Popp et al 2017, Rogelji et al. 2017, van Vuuren et al. 2018, Frank et al. 2018, van Soest et al 2019, Hasegawa et al. 2018). Regional AFOLU GHG emissions in scenarios with >3°C warming in 2100, as shown in Figure 7.13, are shaped by considerable CH_4 and N_2O emissions throughout 2050 and 2100, mainly from ASIA and MAF. CH_4 emissions from enteric fermentation are largely caused by ASIA, followed by MAF, while CH_4 emissions from paddy rice production are almost exclusively caused by ASIA. N_2O emissions from animal waste management and soils are more equally distributed across region.

In most regions, CH_4 and N_2O emission are both lower in 2-3°C and 1.5-2°C mitigation pathways compared to >3°C scenarios (Popp et al 2017, Rogelj et al 2018). In particular, the reduction of CH_4 emissions from enteric fermentation in ASIA and MAF is profound. Land-related CO_2 emissions, which include emissions from deforestation as well as from afforestation, are slightly negative in 2-3°C and 1.5-2°C mitigation pathways compared to >3°C scenarios. Carbon sequestration via BECCS is most prominent in ASIA, LAM, MAF and OECD, which are also the regions with the highest bioenergy area.

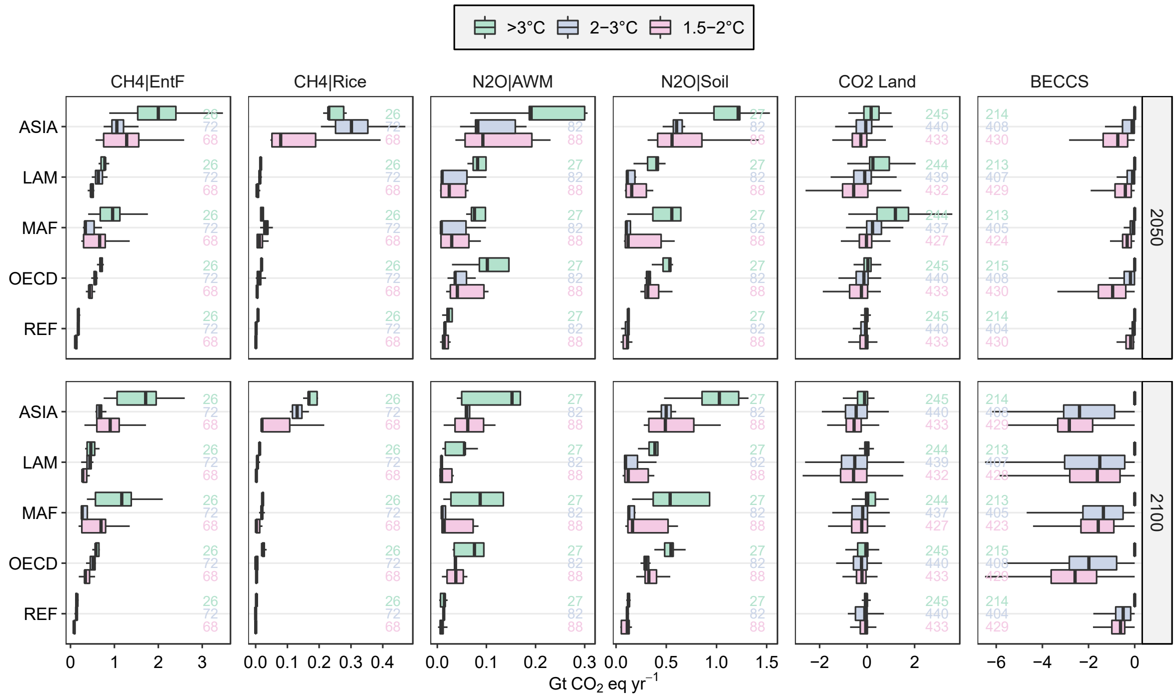


Figure 7.13 Land-based regional GHG emissions and removals in 2050 (top) and 2100 (bottom) for scenarios from the AR6 Database with >3°C, 2-3°C and 1.5-2°C global warming in 2100 (scenario type is indicated by colour). The categories shown include CH_4 emissions from enteric fermentation (EntF) and rice production (Rice), N_2O emissions from animal waste management (AWM) and fertilisation (Soil). The category CO_2 Land includes CO_2 emissions from land-use change as well as negative emissions due to afforestation/reforestation. BECCS reflects the CO_2 emissions captured from bioenergy use and stored in geological deposits. The annual GHG emission data from various models and scenarios is converted to CO_2 equivalents using GWP factors of 28 for CH_4 and 265 for N_2O. The data is summarised in boxplots (Tukey style), which show the median (vertical line), the interquartile range (IQR box) and the range of values within 1.5 x IQR at either end of the box (horizontal lines) across all models and scenarios. The number of data points available for each emission category, scenario type, region and year is shown at the edge of each panel. Regional definitions: ASIA = Asia, LAM = Latin America and Caribbean, MAF = Middle East and Africa, OECD = Developed Countries (OECD 90 and EU), REF = Reforming Economies of Eastern Europe and the Former Soviet Union.

Figure 7.14 indicates that regional land use dynamics in scenarios with >3°C warming in 2100 are characterised by slightly decreasing agricultural land (i.e. cropland and pasture) in ASIA, rather static agricultural land in LAM, OECD and REF, and increasing agricultural land in MAF. Bioenergy area is relatively small in all regions. Agricultural land in MAF expands at the cost of forests and other natural land.

The overall land dynamics in in 2-3°C and 1.5-2°C mitigation pathways are shaped by land-demanding mitigation options such as bioenergy and afforestation, in addition to the demand for other agricultural and forest commodities. Bioenergy production and afforestation take place largely in the (partly) tropical regions ASIA, LAM and MAF, but also in OECD. Land for dedicated second generation bioenergy crops and afforestation displace agricultural land for food production (cropland and pasture) and other natural land. For instance, in the 1.5-2°C mitigation pathway in ASIA, bioenergy and afforestation area together increase by almost 2 million km^2 between 2020 and 2100, mostly at the cost of cropland and pasture (median values). Such large-scale transformations of land use have repercussions on biogeochemical cycles (e.g. fertiliser and water) but also on the economy (e.g. food prices).

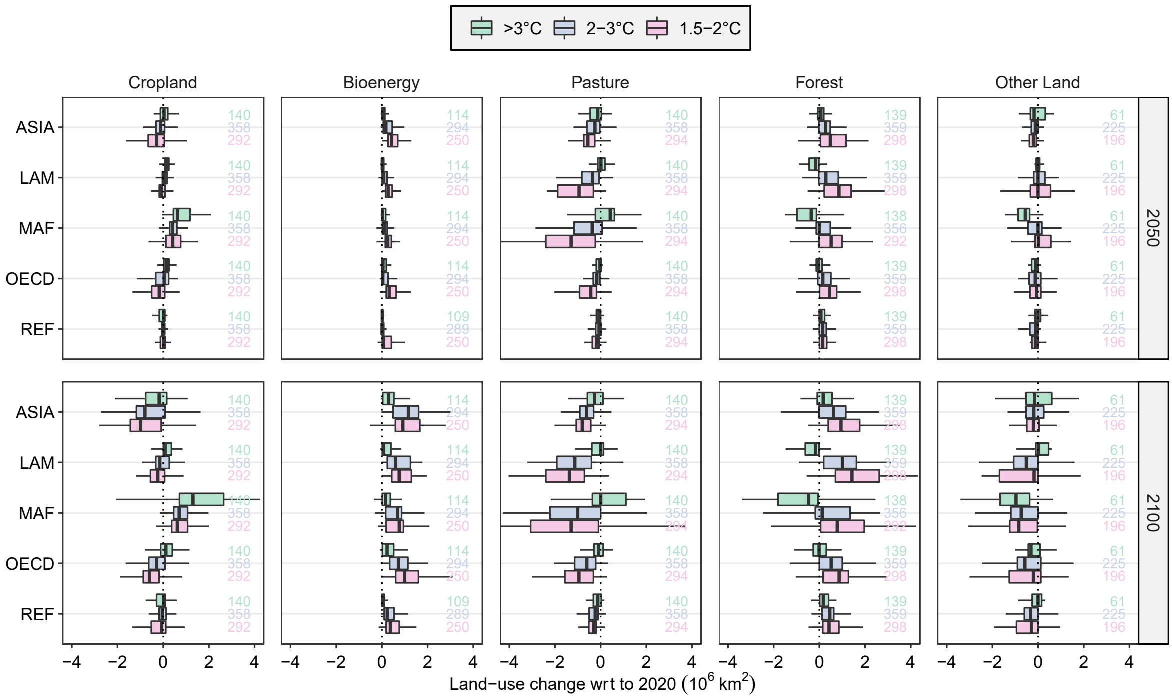


Figure 7.14 Regional change of major land cover types by 2050 (top) and 2100 (bottom) relative to 2020 for scenarios from the AR6 Database with >3°C, 2-3°C and 1.5-2°C global warming in 2100 (scenario type is indicated by colour). The data is summarised in boxplots (Tukey style), which show the median (vertical line), the interquartile range (IQR box) and the range of values within 1.5 x IQR at either end of the box (horizontal lines) across all models and scenarios. The number of data points available for each land cover type, scenario type, region and year is shown at the right edge of each panel. Regional definitions: ASIA = Asia, LAM = Latin America and Caribbean, MAF = Middle East and Africa, OECD = Developed Countries (OECD 90 and EU), REF = Reforming Economies of Eastern Europe and the Former Soviet Union.

7.5.2 Marginal abatement costs according to integrated assessments

In this section, Integrated Assessment Model (IAM) results from the AR6 database are used to derive marginal abatement cost curves (MACCs) which indicate the economic mitigation potential for the different gases (N_2O, CH_4, CO_2) related to the AFOLU sector, at the global level and at the level of five world regions. This review provides a complementary view on the economic mitigation potentials estimated in Section 7.4 by implicitly taking into account the interlinkages between the land-based mitigation options themselves as well as the interlinkages with mitigation options in the other sectors such as BECCS. The review systematically evaluates the uncertainty in the economic potentials estimates across gases, time, and carbon prices.

For different models and scenarios from the AR6 database, the amount of mitigated emissions is presented together with the respective carbon price which has been applied in the same scenario (Figure 7.15). Scenarios have been excluded, if they do not have an associated benchmark scenario or fail the vetting according to the AR6 scenario database, or if they do not report carbon prices and CO_2 emissions from AFOLU. Scenarios with contradicting assumptions (for example, fixing some of the emissions to baseline levels) are excluded. Furthermore, only scenarios with consistent[2] regional and global level results are considered. Mitigation potentials are computed by subtracting scenario specific emissions and sequestration amounts from their respective benchmark scenario values. As some benchmark scenarios apply already low to medium carbon prices, for consistency reasons, the scenario specific carbon prices are corrected by the benchmark prices. This may generate a bias because low carbon prices tend to have a stronger marginal impact on mitigation than high carbon prices. Carbon prices which become negative are not considered.

This approach is close to integrated assessment MACCs as described in the literature (Frank et al. 2018; 2019, Harmsen et al. 2019; Fujimori et al. 2016) in the sense that it incorporates besides the technical mitigation options also structural options triggered by a carbon price, as well as behavioural changes and market feedbacks. Furthermore, indirect emission changes and interactions with other sectors can be highly relevant (Daioglou et al. 2019; Kalt et al. 2020) and are also included in the presented potentials. Hereby, some sequestration efforts can occur in other sectors, while leading to less mitigation in the AFOLU sector. For instance, BECCS sequestration is usually accounted for in the energy system, while it may lead to increasing emissions in the land use sector (Kalt et al. 2020). The strengths of the competition between biomass for energy supply and carbon sequestration in forests will depend on the biomass feedstocks considered, such as forest residues versus dedicated energy plantations (Lauri et al. 2019).

In the individual cases, the accounting of all these effects is dependent on the respective underlying model and its coverage of inter-relations of different sectors and sub-sectors. The presented potentials cover a wide range of models, and additionally, a wide range of background assumptions on macro-economic, technical, and behavioural developments as well as policies, which the models have been fed with. Subsequently, the range of the resulting marginal abatement costs is relatively wide, showing the full range of expected contributions from land use sector mitigation and sequestration in applied mitigation pathways.

FOOTNOTE: [2] Scenarios are considered consistent between global and regional results, if the sum of regional emissions (or sequestration efforts) does not deviate more than 10% from the reported global total. To take into account that small absolute values have a higher sensitivity, a deviation of 90% is allowed for absolute values below 100.

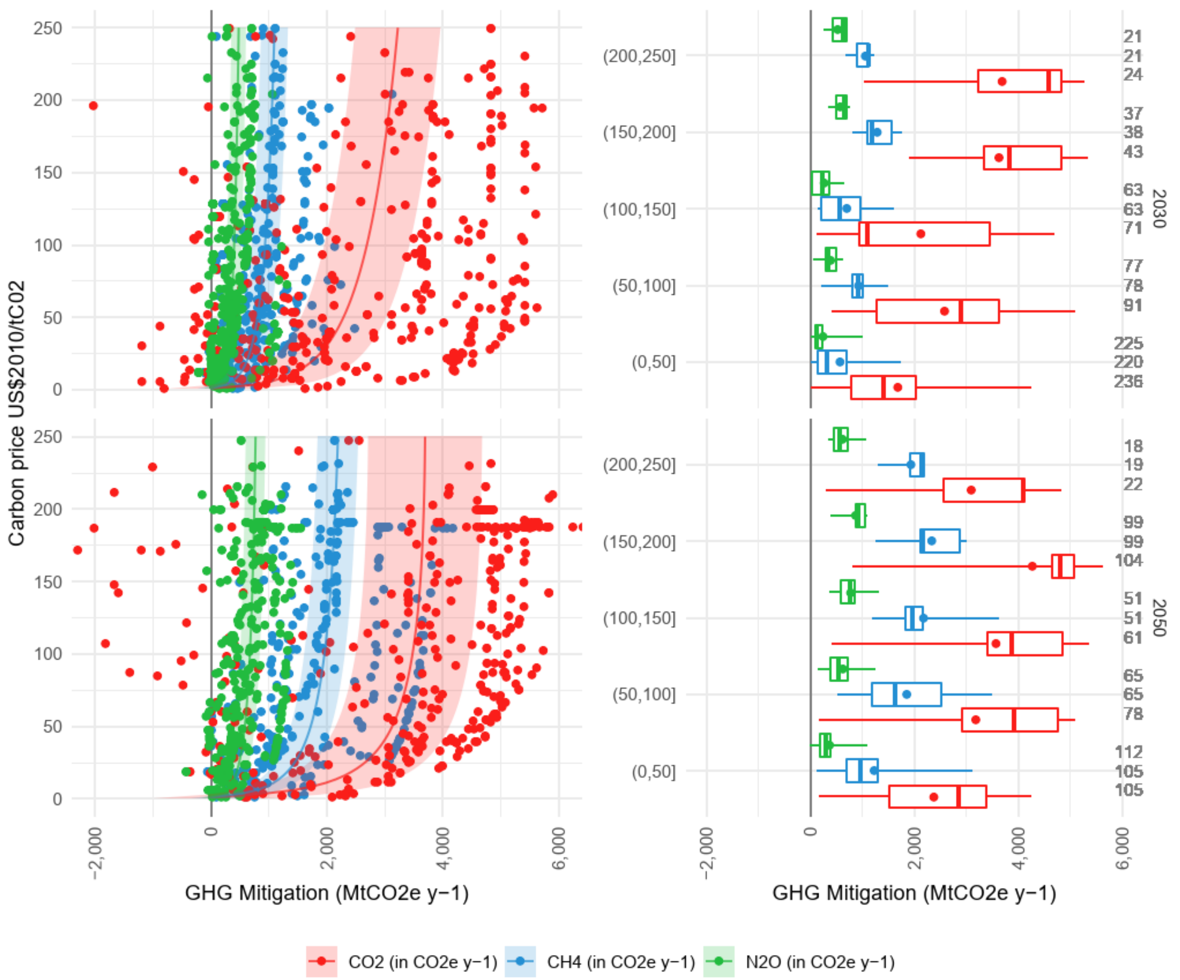


Figure 7.15 Mitigation of CO_2, CH_4 and N_2O emissions (in CO_2-eq yr^{-1} using IPCC AR5 GWP_{100} values) from the AFOLU sector for increasing carbon price levels for 2030 and 2050. In the left side panels, single data points are generated by comparing emissions between a policy scenario and a related benchmark scenario, and mapping these differences with the respective carbon price difference. Plots only show the price range of up to 250USD (2010)/tCO_2-eq and the mitigation range between -2,000 and 6,000 MtCO_2-eq yr^{-1} for better visibility. Fitted trend lines are based on functional forms chosen from 6 options (x, log(x), $\sqrt{x}$, $\sqrt[3]{x}$, log(x)+ $\sqrt{x}$, log(x)+ $\sqrt[3]{x}$) based on the best fit (R^2). Shaded areas represent predictive intervals with significance levels of 33% to preserve readability. A larger range of uncertainty is presented in the panels at the right-hand side. Based on the same data as left-hand side panels, Boxplots show Medians (vertical line within the boxes), Means (dots), 33%-66% intervals (Box) and 10%-90% intervals (horizontal lines). Numbers on the very right indicate the amount of observations falling into the respective price range per variable. [ANALYSIS IS BASED ON SNAPSHOT FROM 14.10.2020].

At the global level, the analysis of the economic mitigation potentials from N_2O and CH_4 emissions from AFOLU (which mainly can be related to agricultural activities) and CO_2 emissions (which mainly can be related to LULUCF emissions) reveals a relatively good agreement of models and scenarios in terms of ranking between the gases. On the right-hand side panels of Figure 7.15, only a few overlaps between the boxes (showing the 33-66% intervals of observations) within the same price ranges can be observed, despite all differences in underlying model structure and scenario assumptions.

N_2O emissions show the smallest economic potential of the three different gases in 2030 as well as in 2050. The mitigation potential increases until a price range of USD 150-200 and to a median value of around 0.5 GtCO_2-eq yr^{-1} mitigation in 2030 and 0.9 GtCO_2-eq yr^{-1} in 2050, respectively, while afterwards with higher prices the expansion is very limited. Mitigation of CH_4 emissions has a higher potential, also with increasing mitigation potentials until a price of around USD 200 in both years, with median mitigation of around 1.2 $GtCO_2$-eq yr^{-1} in 2030 and around 2 $GtCO_2$-eq yr^{-1} in 2050, respectively. The highest mitigation potentials are observed for CO_2, but also the highest ranges of observations among the three gases. In 2030, a median of 4.5 $GtCO_2$-eq yr^{-1} mitigation potential is reported for the price range of USD 200-250. This result, however, is based on relatively few observations. In 2050, for the carbon price range of between USD 150 and USD 200, a median of around 4.8 $GtCO_2$-eq yr^{-1} can be observed.

Marginal mitigation potentials are decreasing faster for CH_4 and CO_2 then for N_2O. The mitigation potential from CH_4 and CO_2 (measured by the medians) in the price range USD 150-200 is only 20-30% higher than the mitigation potential median for the price range USD 50-100, while for N_2O the difference is still 85% and 67% in 2030 and 2050, respectively.

When compared with the sectoral estimates from Harmsen et al. (2019), the integrated assessment median potentials are broadly comparable for the N_2O mitigation potential; Harmsen et al. 2050 mitigation potential at USD 125 is 0.6 $GtCO_2$-eq yr^{-1} while the integrated assessment estimate for the same price range is 0.8 $GtCO_2$-eq yr^{-1}. The difference is substantially larger for the CH4 mitigation potential; 0.9 $GtCO_2$-eq yr^{-1} in Harmsen et al. while 1.9 $GtCO_2$-eq yr^{-1} the median integrated assessment estimate. While the Harmsen et al. MACCs consider only technological mitigation options, integrated assessments typically include also demand side response to the carbon price and GHG efficiency improvements through structural change and international trade. These additional mitigation options can represent more than 60% of the total non-CO_2 mitigation potential in the agricultural sector, where they are more important in the livestock sector, and thus the difference between sectoral and integrated assessments is more pronounced for the CH_4 emissions (Frank et al. 2019).

Economic CO_2 mitigation potentials from land use change and forestry are larger compared to potentials from non-CO_2 gases, and at the same time reveal high levels of uncertainty in absolute terms. The 66th percentile in 2050 goes up to 5 $GtCO_2$-eq yr^{-1} mitigation, while the lowest observations are even negative, indicating higher CO_2 emissions from land use in scenarios with carbon price compared to scenarios without. In relative terms (measured by the coefficient of variation), however, different levels of uncertainty are not clearly distinguishable among the different gases.

Land use is at the centre of the interdependencies with other mitigation measures, including bioenergy. Some models see a strong competition between BECCS deployment with its respective demand for biomass, and CO_2 mitigation/sequestration potentials. Many scenarios rely on large scale bioenergy deployment, which may lead to negative CO_2 mitigation in several scenarios (Daioglou 2019; Luderer et al. 2018, SI) and can explain the high variety of observations in some cases. The large variety of observations shows a large variety of plausible results, which can go back to different model structures and assumptions, showing a robust range of plausible outcomes (Kriegler et al. 2015).

7.5.3 Impacts of SDGs on integrated assessment economic AFOLU mitigation potentials

Besides the level of biomass supply for bioenergy, the adoption of SDGs may also significantly impact, AFOLU emissions and the land use sector's ability for GHG abatement (Frank et al. in press). Selected SDGs are found to have positive synergies for AFOLU GHG abatement and to consistently decrease GHG emissions for both agriculture and forestry, thereby allowing for even more rapid and deeper emissions cuts. In particular, the decreased consumption of animal products and less food waste (SDG12), and the protection of high biodiversity ecosystems such as primary forests (SDG15) deliver high synergies with GHG abatement. However, protecting highly biodiverse ecosystems from conversion (SDG15), could limit global biomass potentials for bioenergy (Frank et al. in press).

7.5.4 Regional marginal abatement costs

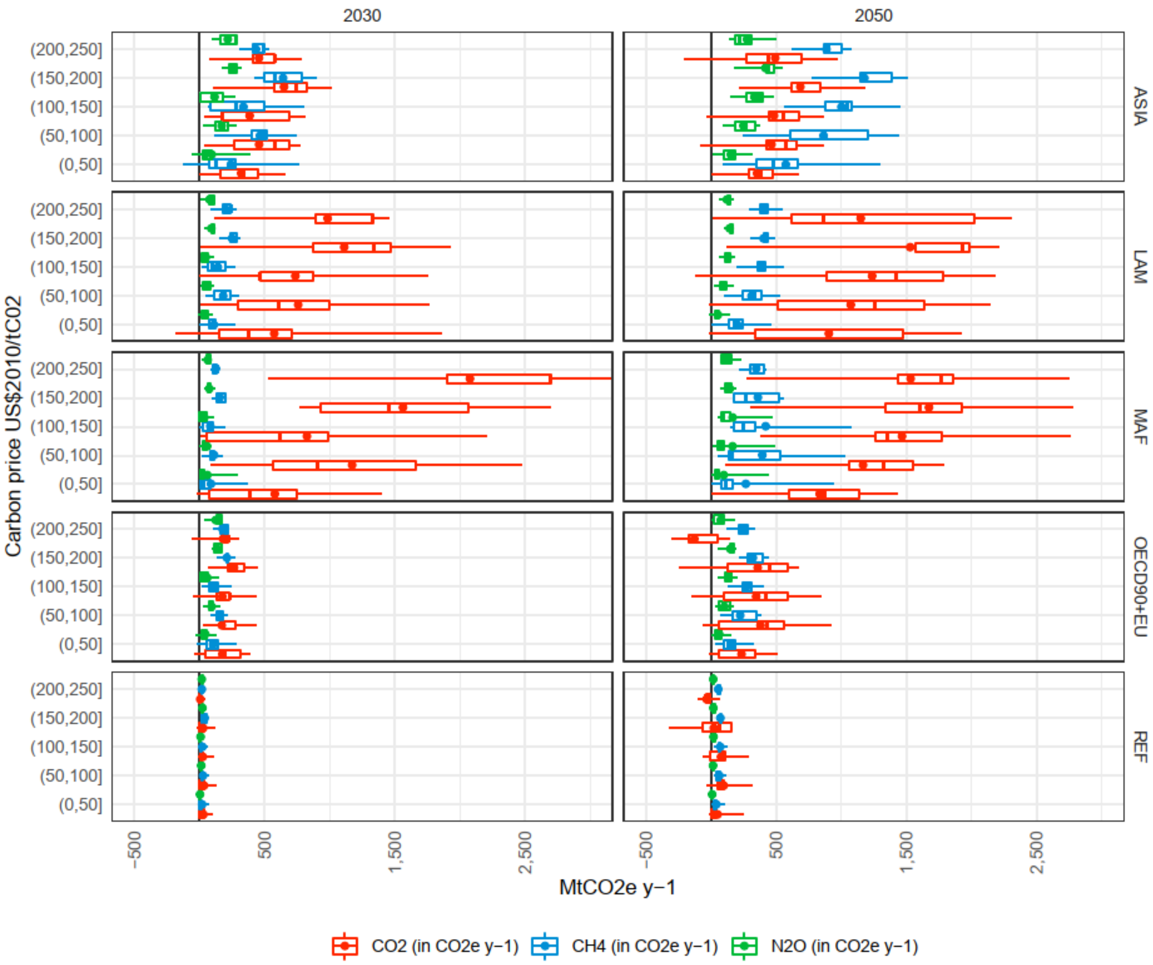


Figure 7.16 Regional mitigation efforts for CO_2, CH_4 and N_2O emissions (in CO_2-eq yr^{-1}) from the AFOLU sector for increasing carbon price levels for 2030 and 2050. Underlying datapoints are generated by comparing emissions between a policy scenario and a related benchmark scenario, mapping these differences with the respective carbon price differences. Boxplots show Medians (vertical line within the boxes), Means (dots), 33%-66% intervals (box) and 10%-90% intervals (horizontal lines). Regions: Asia (ASIA), Latin America and Caribbean (LAM), Middle East and Africa (MAF), Developed Countries (OECD 90 and EU) (OECD+EU) and Reforming Economies of Eastern Europe and the Former Soviet Union (REF). [ANALYSIS IS BASED ON SNAPSHOT FROM 14.10.2020, GLOBAL C PRICES USED].

At the regional level (Figure 7.16), the highest potential from non-CO_2 emissions abatement, and mostly from CH_4, is reported for ASIA with the median of mitigation potential observations from CH_4 increasing up to a price of USD 200 in the year 2050, reaching almost 1.2 $GtCO_2$-eq yr^{-1}. In 2030, the potential would even increase a bit more beyond the presented price ranges in Figure 7.16 (until around USD 300) but based on only very few observations. In terms of economic potential, ASIA is followed by LAM, MAF, and OECD+EU, where emission reduction mainly is achieved in the livestock sector. A good agreement of models can be observed for LAM and OECD+EU, while ASIA and MAF have a wider range of results for non-CO_2 emissions, partly reflecting their absolute size of median observations.

The highest potentials from land-related CO_2 emissions, including avoided deforestation as well as afforestation, can be observed in LAM and MAF with strong responses of mitigation (indicated by the median value) to carbon prices over the whole range of displayed carbon prices. In general, CO_2 mitigation potentials show a wide range of results in comparison to non-CO_2 mitigation potentials, but mostly also a higher median value. The most extreme ranges are reported for the regions LAM and MAF, where the 10%-90% range of observations reaches from 0 to more than 3 $GtCO_2$-eq yr^{-1} in MAF (in 2030, USD 200-250) and 0 to almost 2.5 $GtCO_2$-eq yr^{-1} economic mitigation potential in LAM for carbon prices between USD 200 and USD 250 in the year 2050. A medium potential is reported for ASIA and OECD+EU, while REF has the smallest potential according to model submissions.

7.5.5 Illustrative pathways

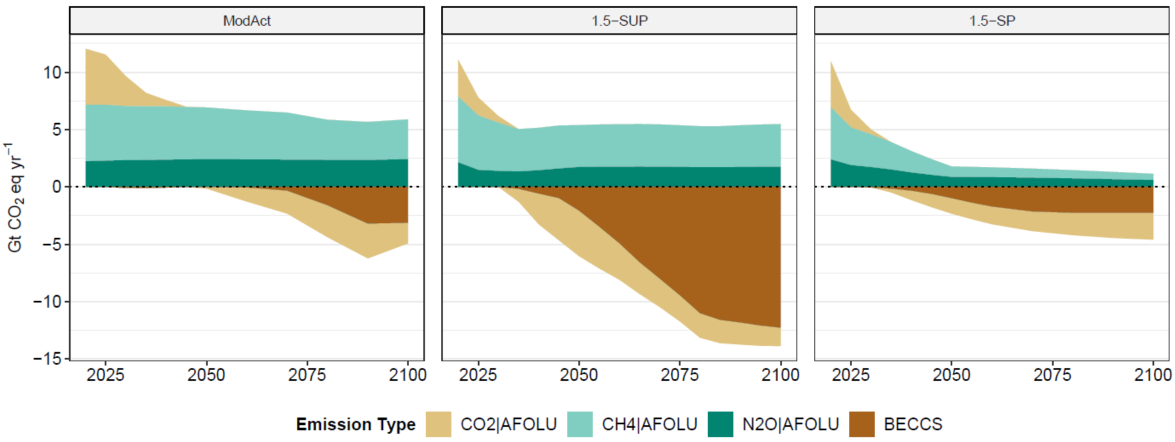
Different mitigation strategies can achieve the net emission reductions that would be required to follow a pathway limiting global warming, with very different consequences for the land system. Figure 7.17 shows illustrative pathways (IPs) for achieving different climate targets highlighting AFOLU mitigation strategies, resulting GHG and land use dynamics as well as the interaction with other sectors. For consistency this chapter discusses IPs as described in detail Chapters 1 and 3 of this report but focusing on the land-use sector. All pathways are assessed by different IAMs and do not only reduce GHG emissions but also use Carbon Dioxide Removal (CDR) options, whereas the amount and timing varies across pathways, as do the relative contributions of different land-based CDR options.

The IP *ModAct* (REFERENZ) is based on the prolongation of current trends (SSP2) but contains measures to strengthen policies for the implementation of National Determined Contributions (NDCs) in all sectors including AFOLU (Grassi et al. 2019). This pathway shows a strong decrease of CO_2 emissions from land-use change in 2030, mainly due to reduced deforestation, as well as moderately decreasing N_2O and CH_4 emissions from agricultural production due to improved agricultural management and dietary shifts away from emissions-intensive livestock products. However, in contrast to CO_2 emissions, which turn net-negative around 2050 due to afforestation/reforestation, CH_4 and N_2O emissions persist throughout the century due to difficulties of eliminating these residual emissions based on existing agricultural management methods (Stevanović et al. 2017; Frank et al. 2017b). Comparably small amounts of BECCS are applied by the end of the century. Forest area increases at the cost of other natural vegetation.

IP *1.5-SUP* (REFERENZ) is similar to IP *ModAct* in terms of socio-economic setting (SSP2) but differs strongly in terms of the mitigation target (RCP1.9). Consequently, all GHG emission reductions as well as afforestation/reforestation and BECCS-based CDR start earlier in time at a higher rate of deployment. However, in contrast to CO_2 emissions, which turn net-negative around 2030 due to afforestation/reforestation, CH_4 and N_2O emissions persist throughout the century due to ongoing increasing demand for total calories and animal based commodities (Bodirsky et al. 2020) and difficulties of eliminating these residual emissions based on existing agricultural management methods (Stevanović et al. 2017; Frank et al. 2017b). In addition to abating land related GHG emissions as well as increasing the terrestrial sink, this example also shows the importance of the land sector in providing biomass for BECCS and hence CDR in the energy sector. Cumulative CDR (2020-2100) amounts to 474 $GtCO_2$ for BECCS and 166 $GtCO_2$ for afforestation. In consequence, compared to IP *ModAct*, much more other natural land as well as agricultural land (cropland and pasture land) is converted to forest or bioenergy cropland with potentially severe consequences for various sustainability dimensions such as biodiversity (Hof et al. 2018) and food security (Fujimori et al. 2019).

In contrast to *IP 1.5-SUP, IP 1.5-SP* (REFERENZ) displays a future of generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant but sustainable agricultural intensification in combination with high levels of nature protection. This pathway shows a strong near-term decrease of CO_2 emissions from land-use change, mainly due to reduced deforestation, as well as strongly decreasing N_2O and CH_4 emissions from agricultural production due to improved agricultural management but also based on dietary shifts away from emissions-intensive livestock products as well as lower shares of food waste. In consequence, comparably small amounts of land are needed for land demanding mitigation activities such as BECCS and afforestation. In particular, the amount of agricultural land converted to bioenergy cropland is smaller compared to other mitigation pathways. Forest area increases either by regrowth of secondary vegetation following the abandonment of agricultural land or by afforestation / reforestation at the cost of agricultural land.

A



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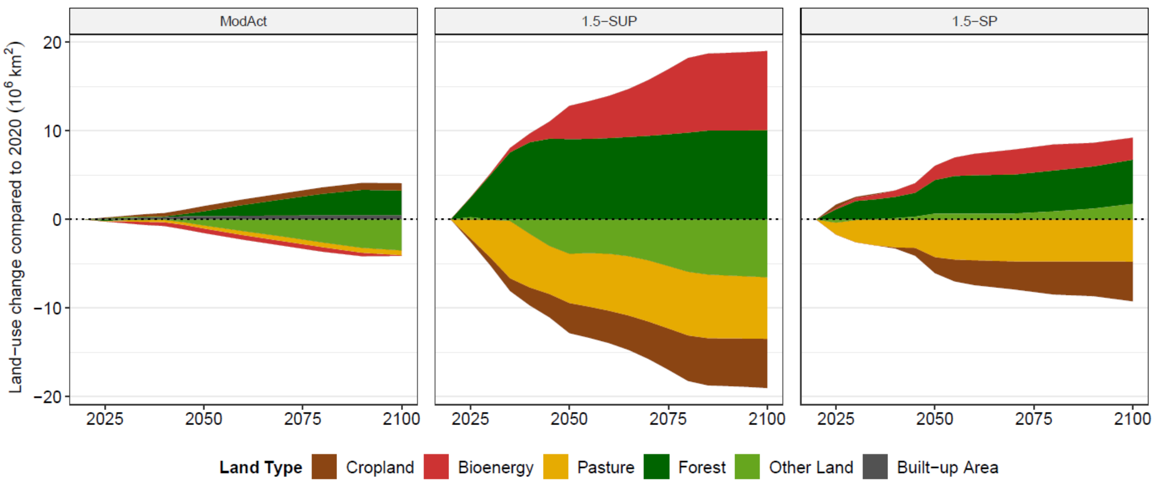

Figure 7.17 Evolution and break down of (A) global land-based GHG emissions and removals and (B) global land use dynamics under three Illustrative mitigation Pathways, which illustrate the differences in timing and magnitude of land-based mitigation approaches including afforestation and BECCS. All pathways are based on different IAM realisations: IP ModAct: SSP2 from IMAGE (REFERNCE); Pathway 2: SSP2 from AIM (REFERNCE); Pathway 3: REMIND-MAgPIE (Soergel et al. submitted); In panel A 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 / reforestation. BECCS reflects the CO_2 emissions captured from bioenergy use and stored in geological deposits. CH_4 and N_2O emissions are converted to CO_2-eq using GWP_{100} factors of 28 and 265 respectively.

7.6 Assessment of economic, social and policy responses

7.6.1 Historical Trends in policy efforts to stimulate AFOLU Mitigation Efforts

Since the establishment of the UNFCCC, international agencies, countries, sub-national units and NGO's have developed a number of policies to facilitate and encourage GHG mitigation within AFOLU (Figure 7.18). Early policy focused on developing GHG inventory methodology with some emphasis on afforestation and reforestation projects, but the emergence of the Clean Development Mechanism (CDM) following the Kyoto Protocol shifted focus towards emission reduction projects, notably projects (outside AFOLU) in developing countries. As the potential for AFOLU mitigation was shown to be large in successive IPCC WGIII reports, efforts to develop methods to quantify and validate carbon emission reductions within related projects intensified in the early 2000s. In particular, methods developed with the formation of voluntary markets, such as the Chicago Climate Exchange (CCX) and regulated markets (New South Wales and California).

Following the COP meeting in Bali, effort shifted to developing policies to reduce deforestation and forest degradation (REDD+). According to Simonet et al. (2019), nearly 65 Mha have been enrolled in REDD+ type projects funded through a variety of mechanisms including UN REDD, the World Bank Forest Carbon Partnership Facility, and bi-lateral agreements between countries (e.g. Norway). While there has been considerable focus on forest and agricultural project-based emission reductions, national governments were encouraged to incorporate project-based approaches with other sectoral strategies in their Nationally Appropriate Mitigation Strategies (NAMAs) after 2012. NAMAs reflect the country's proposed strategy to reduce net emissions across various sectors within their economy (e.g. forests or agriculture). More recently, Nationally Determined Contributions (NDCs) indicate whether individual countries plan to use forestry and agricultural policies or related projects to reduce their net emissions as part of the Paris Accord.

Figure 7.18 Milestones in policy development for AFOLU measures.

The many protocols now available can be used to quantify the emission reduction to date from these projects. For instance, carbon registry programs produce credits that account for additionality, permanence and leakage, thus providing evidence that the projects are a net carbon benefit to the atmosphere. Protocol development engages the scientific community, project developers, and the public over a multi-year period. Some protocols have been revised multiple times, such as the California forest carbon protocol, which is in its 5th revision, with the latest in 2019 (see http://www.climateactionreserve.org/how/protocols/forest/). Credits from carbon registries feed into regulatory programs, such as the cap and trade program in California in the United States, or voluntary offset markets (Hamrick and Gallant 2017). Although AFOLU measures have been deployed across a range of projects and programs globally to reduce net carbon emissions, debate about the net carbon benefits of some project types continues (e.g. Krug 2018).

An assessment of approaches over the last two decades finds that at least 8.1 $GtCO_2$-eq (using GWP_{100} and a mix of IPCC values for CH_4 and N_2O) have been offset over the last 12 years due to agricultural and forestry activities (Table 7.9). More than 80% of these offsets have been generated by forest-based activities. The total amounts to 0.65 $GtCO_2$ yr^{-1} for the period 2010-2019, which is 1.4% of global gross emissions and 11.7% of AFOLU emissions reported in Table 7.1, over the same time period (*high confidence*).

The array of activities in Table 7.9 includes the Clean Development Mechanism, REDD+ activities reported in technical annexes of country biennial reports, voluntary market transactions, and carbon stored as a result of carbon markets in Australia, New Zealand and California. Although other countries and sub-national units have developed programs and policies (Box 7.11), these three regions are presented due to their focus on forest and agricultural carbon mitigation, their use of generally accepted protocols or measures and the availability of data to quantify outcomes.

The largest share of carbon offsets in Table 7.9 has been derived from REDD+ efforts, and specifically from efforts in Brazil, which substantially reduced deforestation rates between 2004 and 2012 (Carvalho et al. 2019), as well as other countries in Latin America. With the exceptions of Simonet et al. (2018) and Roopsind et al. (2019), all of the REDD+ estimated reductions in carbon emissions are measured relative to a historical baseline. As noted in Brazil's Third Biennial Report (Ministry of Finance 2019), estimates are made in accordance with approved UNFCCC methodologies and were made to determine the benefits of results-based REDD+ payments to Brazil. Estimates from other countries have similarly been derived from country level biennial reports.

Regulatory markets provide the next largest share of carbon removal to date. Data from the Australia Emissions Reduction Fund is an estimate of carbon credits in agriculture and forestry purchased by the Australian government to be used to offset emissions in other sectors. In the case of California, offset credits from forest and agricultural activities, using methods approved by a third-party certification authority (Climate Action Reserve), have been allowed as part of their state-wide cap and trade system. Transaction prices in California have recently been around USD 13/tCO_2 for forest and agricultural credits in 2018 and represented 7.4% of total market compliance. By the end of 2018, 80 $MtCO_2$ had been used for compliance purposes.

New Zealand has several ways in which agriculture and forestry can participate in carbon markets. Table 7.9 however, contains credits only from post-1989 forests that were voluntarily entered into the trading program. Unlike offsets in voluntary markets or in California, where permanence involves long-term contracts or insurance pools, forests in the New Zealand market liable for emissions when harvested or following land use change. Offset prices were around USD 13/tCO_2 in 2016 but have risen to more than USD 20/tCO_2 in 2020.

The voluntary market data is obtained from Hamrick and Gallant (2017) and refers to voluntary forest and land use offsets that have been retired. Most of these credits have been produced using protocols developed by the main accreditation organisation. Retired credits can no longer be sold and have been used either to offset a specific level of emissions, or they have been retired for environmental purposes. The number of retired forest and land use credits is about half of the total credits that were generated for voluntary markets over the time period.

Voluntary offset markets have continued to grow and over 100 MtCO_2 in AFOLU projects were sold from 2010-2018 (Table 7.9). The largest share of annual sales of voluntary AFOLU credits occurs in Latin America, followed by Africa, Asia and North America. Europe and Oceania have smaller voluntary carbon markets. Most volume lies in avoided deforestation projects, with some volume accruing to afforestation and improved forest management. Prices for these offsets in the period 2014-2016 ranged from USD 4.90 to USD 5.40/tCO_2, with highest prices in Europe, North America, and Oceania (Hamrick and Gallant 2017).

Voluntary finance has been similar in scale, providing USD 1.6 billion over a 10-year period for development of credits to be used in voluntary markets. The three regulatory markets quantified amount to USD 2.7 billion in funding from 2010 to 2019. For the most part, this funding has focused on forest projects and programs, with agricultural projects accounting for 5-10% of the total. In total, reported funding for AFOLU projects and programs has been USD 5.5 billion over the past decade, or about USD 679 million yr^{-1} (*low confidence*). A large portion of the total carbon includes efforts in the Amazon by Brazil, and government expenditures on regulatory programs, business expenditures on voluntary programs were not included in cost estimates due to difficulties obtaining that data. If Brazil and CDM (for which we have no cost estimates) are left out of the calculation, average cost per ton has been USD 3.20/tCO_2.

Table 7.9 Achieved emissions reductions in AFOLU through 2018

Fund / Mechanism	Total Emission Reductions (Mt CO_2-eq)	Time Frame	Mt CO_2-eq yr^{-1}	Financing (Million USD yr^{-1})
CDM-forest[1]	11.3	2007-2015	1.3	-
CDM-agriculture[1]	21.8	2007-2015	2.4	-
REDD+ (Guyana)[2]	12.8	2010-2015	2.1	33.0
REDD+ Brazil[3]	6,894.5	2006-2017	574.5	49.2
REDD+Indonesia[3]	244.9	2013-2017	49.0	13.4
REDD+Argentina[3]	165.2	2014-2015	55.1	1.4
REDD+Others[3]	211.8	2010-2017	26.5	46.0
Voluntary Market[4]	307.4	2009-2018	30.7	156.6
Australia ERF[5]	33.7	2012-2018	4.8	50.5
California[6]	122.2	2013-2018	20.4	227.1
New Zealand Carbon Trading[7]	83.9	2010-2019	8.4	101.7
Total	**8,109.5**	**2007-2018**	**675.8 [8]**	**678.8**

[1] Clean Development Mechanism Registry: https://cdm.unfccc.int/Registry/index.html
[2] Roopsind et al. 2019

[3] UNFCCC REDD+ Web Platform (https://redd.unfccc.int/submissions.html) and UNFCCC Biennial Report database (https://unfccc.int/BURs)
[4] Hamrick, K and Gallant, M. 2017. State of Forest Carbon Finance. Forest Trends Ecosystem Marketplace. Washington, DC.
[5] Data from Australia Emission Reduction Fund Registry for forest agricultural and savanna practices (http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register)
[6] Data from the California Air Resources Board Offset Issuance registry (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program) for forestry and agricultural early action and compliance credits
[7] Surrendered forest carbon credits from post-1989 forests in New Zealand. Environmental Protection Authority. 2017 New Zealand Emissions Trading Scheme Facts and Figures 2017. New Zealand Government.
[8] All non-CO_2 gasses are converted to CO_2-eq using IPCC GWP_{100} values recommended at the time the project achieved approval by the relevant organisation or agency.

Box 7.11 The challenge: micro-level design of policies needed

Background

The world has never before seen such an impressive scale of policy experimentation and instruments from which to choose. These include the development of a rich suite of innovative "finance and market" (FMD) driven interventions, ranging from international financing mechanisms such as the Global Environmental Facility (GEF) to climate bonds, to a plethora of non-state market driven (NSMD) eco-labelling programs governing commodity production, to corporate social responsibility initiatives. (Park 2007; Auld et al. 2017; Clapp 1998). This international window is certainly present. The global community, and the EU, is devoting considerable attention, and resources, to targeting specific gaps in SDG implementation including the climate and biodiversity crisis. However, implementation and persistence remain a challenge

Given this, it is clear that the vast majority of policy design to date has been developed in ways that have failed to meaningfully address the climate crisis in general, and the role of agriculture and forests in particular. These include billions spent on what were now widely understood as sanguine expectations (Streck et al. 2009; Parker et al. 2009) of REDD+ efforts some of which, over a decade later, have failed to materialise in any significant manner. They also include previous efforts at supply chain governance with varying success (Forest Stewardship Council 1996; Subak 2002) and likewise, the seemingly growing belief that protecting community forestry will always benefit climate challenges (Lawlor et al. 2013; Duchelle et al. 2014).

Case Description

At the same time, we can identify a number of cases around the world that illustrate the benefits of a wider policy analysis and that carry historical lessons. One example is the 1990s British Columbia Protected Areas Policy. During the mid-1990s a newly elected government promised to implement Brundtland inspired norms of 12% protection of land from commodity interests. The approach drew on both top down and bottom up processes. The "top down" approach mandated the doubling of protected areas from 6-12% of the provinces' land base, and to implementing an "instrument logic", a "command and control" and a "line on map" regulatory approach. Finally, a "micro level" design was set up that led to decisions that were also highly durable 25 years later. Instructions to local stakeholder processes gave them two years to achieve a solution. They were further told that if they did not agree within two years, a solution would be imposed on them. These deliberations over causal impact, rather than simply focused on compromise or interest-based approaches, appears to have created the conditions in which legitimacy and norms of appropriateness permeated the deliberative arenas and helped account for what are durable change processes 25 years later (Marchak et al. 2002)

Lessons

Lessons from this example could be applied to a wide variety of cases, from conservation efforts in Southeast Asia, Latin American and Africa. Further, by taking into account historical political and economic differences, the approach also applies micro level design to macro level transformative expectations (Cashore and Bernstein 2018).

7.6.2 Review of policy instruments

7.6.2.1 Economic incentives

Emissions Trading/Carbon Taxes. While emissions trading programs have been developed across the globe, forest and agriculture have not been included as part of the cap in any of the existing systems. However, offsets from forestry and agriculture have been included in several of the trading programs. New Zealand has a hybrid program where carbon storage in forests can be voluntarily entered into the carbon trading program, but once entered, forests are counted both as a sink for carbon if net gains are positive, and a source when harvesting occurs. New Zealand is also considering rules to include agricultural GHG emissions under a future cap.

In the United States, California has developed a formal cap and trade program that allows forest and agricultural offsets to be used under the cap. All offsets must meet protocols to account for additionality, permanence and leakage. Forest projects used as off-sets in California currently are located in the US, but the California Air Resources Board adopted a tropical forest carbon standard, allowing for avoided deforestation projects from outside the US to enter the California market (https://ww3.arb.ca.gov/cc/ghgsectors/tropicalforests/ca_tropical_forest_standard_english.pdf).

Canadian provinces have developed a range of policy options that can include carbon offsets. Quebec has an emissions trading program that allows forest and agricultural offsets generated within the province to be utilised. Alberta also allows offsets to be utilised by regulated sectors while British Columbia allows offsets to be utilised by the government for its carbon neutrality goals.

Over 20 countries and regions have adopted explicit carbon taxes on carbon emission sources and fossil fuels, however, the charges have not been applied to non-CO_2 agricultural emissions (OECD 2018; OECD 2019). California is considering implementing regulations on methane emissions from cattle, however, regulations if approved, will not go into effect until 2024. Importantly, some countries have exempted purchases of fuels used in agricultural or fishery production, thus lowering the effective tax rate imposed on those sectors (OECD 2019). Furthermore, bioenergy, produced from agricultural products, agricultural waste, and wood is exempted from explicit carbon taxes in most countries.

REDD+/*Payment for Ecosystem Services (PES).* REDD+ emerged as a critical funding source for conservation of tropical forests after the COP at Bali in 2006. As a funding mechanism, REDD+ operates like a Payment for Ecosystem Services, or PES, program. PES programs have long been utilised for forest conservation (e.g. Wunder 2007) and in across a wide range of programs now may be as large as USD 42 billion yr^{-1} (Salzman et al., 2018). REDD+ may operate at the country level, or for specific programs or forests within a region of a country. As with PES programs, REDD+ has evolved into a results-based program that involves payments that are conditioned on meeting certain successes or milestones, such as maximum rates of deforestation during a given period (Angelsen 2017).

A large literature has investigated whether PES programs have successfully protected habitat. Studies in the US found limited additionality for programs that encouraged conservation tillage practices, but stronger additionality for programs that encouraged set-asides for grasslands or forests (Woodward et al., 2016; Claasen et al., 2018), although the set-asides led to an estimated 20% leakage (Wu et al. 2000; Pfaff and Robalino 2018). Other studies, in particular in Latin America where many PES programs have been implemented, have found a wide range of estimates of effectiveness (e.g. Honey-Roses et al. 2011; Robalino and Pfaff 2013; Alix-Garcia et al. 2015; Mohebalian and Aguilar 2016; Robalino et al. 2015; Jayachandran et al. 2017; Borner et al. 2017; Burivalova et al. 2019). Despite concerns over which land has received payments and potential leakage, enough lessons have been learned from past PES program implementation to provide critical direction to refine future efforts in ways that can support an increase in carbon sequestration (*medium confidence*).

Total REDD+ funding dispersed to date is estimated to be USD 1.3 billion. These funds have been allocated through a variety of international organisations. REDD+ investments through the United Nations REDD+ programs were USD 277 million in 64 countries from 2008 to 2018 (UN REDD Programme, 2018). The World Bank Forest Carbon Partnership Facility disbursed USD 200 million over the period 2010-2019 in 47 countries (FCPF Annual Report, 2019). Neither of these two mechanisms has yet paid for actual carbon reductions, with most funds having been used for capacity building and readiness programs. Thus, actual payments to the forest or landowner have been minimal. The Amazon fund in Brazil dispersed USD 491 million from 2008-2018, with results-based payments (Amazon Fund Annual Report, 2019). Guyana and Indonesia also received readiness funds and results-based funds totalling USD 265 million (Roopsind et al. 2019).

Significant additional funding is available to generate reductions in net carbon emissions through REDD+ with existing sources. The Amazon Fund has an additional USD 200 million available for allocation. However, disagreements between the Brazilian federal government and the main donors, Norway and Germany, on the governance resulted in the fund's suspension (Hecht, 2020, see Box 7.12). The World Bank FCPF reports USD 141 million in readiness funds yet to be dispersed and USD 900 million in funds available for results-based payments. The Green Climate Fund has over USD 6 billion in projected disbursements for a range of projects, many of which will increase carbon storage in developing countries.

While the expectations that carbon-centred REDD+ would be a simple and efficient mechanism for climate mitigation have not been met (Turnhout et al. 2017; Arts et al. 2019), progress has nonetheless occurred to date. Improved measuring, monitoring and verification systems have been developed and deployed, REDD readiness programs have improved capacity to implement REDD+ on the ground in over 50 countries around the world, and at least three countries have received results-based payments for efforts to date (Brazil, Indonesia and Guyana).

Empirical evidence that REDD+ funding has slowed deforestation is starting to emerge. Simonet et al., (2018) examined the effects of REDD+ projects in Brazil and found that they had reduced deforestation, while Roopsind et al., (2019) assessed whether country-level REDD+ payments to Guyana encouraged reduced deforestation and increased carbon storage. Although more impact evaluation (IE) analysis needs to be conducted on REDD+ payments, these early results support country level estimates in Table 7.9 suggesting that REDD+ has slowed deforestation and provided carbon benefits to date (*medium confidence*). Nearly all of the IE analysis of PES and REDD+ so far has focused on the presence or absence of forest cover so far, with little to no analysis having been conducted on forest degradation.

Agro-environmental Subsidy Programs/PES. The slow development of climate policy for agriculture compared to other sectors concerns food security and livelihoods, political interests, and the difficulties in coordinating diffuse and diverse activities and stakeholders (e.g. nutritional health, rural development, and biodiversity conservation) (Leahy et al. 2020). Despite that, the comparison of the preparation processes of the National Adaptation Programme of Action (NAPAs), National Adaptation Plans (NAPs) and Nationally Appropriate Mitigation Actions (NAMAs), and the analysis of NDCs in the Paris Agreement, indicated that an increasing focus is on agriculture and food security. The vast majority of Parties in the Paris Agreement recognise the significant role of agriculture in supporting a secure sustainable development pathway (Richards et al. 2015) with the inclusion of agriculture mitigation in 103 submissions from a total of 160 Party submissions. Livestock was the most frequently cited specific agricultural sub-sector, with mitigation activities generally focusing on increasing efficiency and productivity.

Agriculture is one of the most subsidised industries globally, especially in the European Union and the United States. In the last 20 years, subsidy payments have shifted to some extent to programs designed to reduce the environmental impact of the agricultural sector. Under the Common Agricultural Policy in the EU, up to 30% of the direct payments to farmers (Pillar 1) have been green payments (Henderson et al., 2020), including some actions that could increase carbon storage, or otherwise reduce emissions. Similarly, at least 30% of the rural development payments (Pillar 2) are used for measures that reduce environmental impact, including reduction of GHG emissions and carbon storage. Although no causal link can be inferred, greenhouse gas emissions have declined 20% from the agricultural sector between 1990 and 2018 (EuroStat 2020).

The United States annually spends USD 4 billion on conservation programs, or 12% of net farm income (US Department of Agriculture 2020). In real terms, this expenditure has remained constant for the last 15 years. The payments support 12 Mha of permanent grass or woodland cover in the Conservation Reserve Program (CRP), which has increased soil carbon sequestration by 3 tCO_2 ha^{-1} yr^{-1} (Paustian et al. 2019; Conant et al. 2017). In addition, the payments support nutrient management programs and other practices. GHG Emissions from the agricultural sector in the US, however, have increased since 1990 (US EPA, 2020). These increases have resulted from a reduction in the area of land in the US CRP program, but also changes in crop rotations, both of which have caused soil carbon stocks to decline (US EPA 2020; Zu et al. 2020). When combined with increased non-CO_2 gas emissions the emission intensity of US agriculture has increased from 1.5 to 1.7 tCO_2 ha^{-1} between 2005 and 2018 (*high confidence*).

China has implemented large conservation programs that have influenced carbon stocks. For example, the Sloping Land Conversion Program combined with other programs has increased forest cover and carbon stocks (*high confidence*), as well as reduced erosion and increased other ecosystem services in China in recent years (Ouyang et al. 2016). Brazil has developed subsidy programs aimed at reducing greenhouse gas emissions from agriculture, and in particular from the animal agriculture industry. Estimates by Manzato et al. (2020) suggest that the program may have reduced agricultural emissions by 169 $MtCO_2$ between 2010 and 2020.

7.6.2.2 Regulatory approaches

Regulations on land use include direct controls on how land is used, zoning, or legally set limits on converting land from one use to another. Since the early 2000s, Brazil has deployed various regulatory measures to slow deforestation, including enforcement of regulations on land use change in the legal Amazon area. Enforcement of these regulations, among other approaches is credited with encouraging the large-scale reduction in deforestation and associated carbon emissions after 2004 (Nepstad et al. 2014). Empirical evidence has found that regulations reduced deforestation in Brazil (Arima et al. 2014) but over time, reversals occurred if there was not consistent enforcement (Azevedo et al. 2017) (Box 7.12).

Several OECD countries have strong legal frameworks that influence agricultural and forest management on both, public and private land. These include for example, legal requirements to protect endangered species, implement conservation tillage, protect riparian areas, replant forests after harvest, maintain historical species composition, forest certification, and other approaches. The extent to which the combined influence of these regulations has enhanced carbon storage in ecosystems is not quantified although they are likely to explain some of the persistent carbon sink that has emerged in temperate forests of many OECD countries (*high confidence*). In the least developed and developing countries, regulatory approaches often face challenges related to lack of priority for environmental issues due to persistent socioeconomic problems (e.g., poverty, opportunity, essential services) and weak governance (Mayer Pelicice 2019; Walker et al. 2019).

Set asides and protected areas have been a widely utilised approach for conservation, and according to FAO (2020), 726 Mha of forests are in protected areas globally, or about 18%. A review of land sparing and land sharing policies in developing countries indicated that most of them follow land sparing models, sometimes in combination with land sharing approaches. However, there is still no clear evidence of which policy provides the best results for ecosystem services provision, conservation, and livelihoods (Mertz and Mertens, 2017). The literature contains a wide range of results on the effectiveness of protected areas to reduce deforestation (Burivalova et al., 2019), with studies suggesting that protected areas provide significant protection of forests (e.g., Blackman et al. 2015), modest protection (Andam et al. 2008), as well as increases in deforestation (Blackman 2015) and possible leakage of harvesting to elsewhere (Kallio and Solberg 2018). An estimate of the contributions of protected areas to mitigation between 2000 and 2012, showed that in the tropics, PAs reduced carbon emissions from deforestation by 4.88 Pg, or around 29%, when compared to the expected rates of deforestation. The tropical Americas (368.8 TgC y−1) responded for the most significant contribution, followed by Asia (25.0 TgC y−1) and Africa (12.7 TgC y−1). Local factors have an important influence on the effectiveness of protected areas (Bebber and Butt 2017). In the Brazilian Amazon, protected area effectiveness is impacted by government agency (federal indigenous lands, federal PAs, and state PAs) (Herrera et al. 2019). Because protected areas may drastically limit less intrusive economic activity, such as logging or harvesting non-timber forest products, they may be relatively costly approaches for forest conservation (*medium confidence*).

Community forest management (CFM) allows less intensive use of forest resources, while at the same time providing carbon benefits by protecting forest cover. Community forest management provides property rights to communities to manage resources in exchange for their efforts to protect those resources. In many cases, the local communities are indigenous people who otherwise may have insecure tenure due to an advancing agricultural frontier or mining activity. According to the Rights and Responsibilities Initiative (RRI, 2018), the area of forests under community management increased globally by 152 Mha from 2002 to 2017, with over 500 Mha under community management in 2017. Studies have now shown that improved property rights with community forest management can reduce deforestation and increase carbon storage (Bowler et al. 2012; Alix-Garcia 2007; Alix-Garcia et al. 2005; Deininger and Minten 2002; Blackman 2015; Fortmann et al. 2017; Burivalova et al. 2019). Efforts to expand property rights, especially community forest management, have likely reduced carbon emissions from deforestation in tropical forests in the last two decades (*high confidence*), although the extent of carbon savings has not been quantified globally.

Environmental regulation of greenhouse gases or their precursors. Regulations can come in many different forms, including explicit rules that limit agricultural inputs (e.g., nitrogen fertiliser), limit emissions from agricultural production (e.g., methane), or require specific technology be used in agricultural or forestry production (e.g., best management practices/BMPs). A recent review of agricultural policies in numerous countries illustrates that few explicit greenhouse gas regulations have been implemented within the agricultural sector (Henderson et al., 2020). While regulations are scarce, a number of countries and regions (e.g., the EU) have agreed to explicit targets to reduce greenhouse gas emissions from the agricultural sector in the future, often focusing on reducing chemical nitrogen use by the agricultural sector. For the most part, targets are to be met with approaches that use subsidies rather than explicit regulation of the agricultural sector.

New Zealand appears to be one of the first OECD countries to explicitly regulate nitrogen applications, as they passed regulations in 2020 to set a per hectare limit on synthetic nitrogen application by farmers and to require fertiliser companies to report sales. This follows implementation of a successful nitrogen pollution trading system to manage nitrogen in the Lake Taupo catchment (Kerr et al. 2015). The Netherlands has similarly developed a phosphorus trading approach to limit phosphorus emissions from agriculture. Although phosphorus does not contribute to climate change directly, by raising production costs for farmers, it could reduce herd size in the Netherlands, and indirectly lower emissions.

Bioenergy targets. Multiple policies have been enacted at national and supra-national levels to promote the use of bioenergy. The main motivation for these policies is to decarbonise the energy system by promoting low carbon energy sources. For bioenergy, the main focus is on the promotion of biofuels to be used by the transport sector, and a smaller focus on bioelectricity production. These policies work by mandating or incentivising the production and use of bioenergy. In the past few years, policies have been proposed, put in place or updated in Australia (Renewable Energy Target), Brazil (RenovaBio, Nationally Determined Contribution), Canada (Clean Fuel Standard), China (Biodiesel Industrial Development Policy, Biodiesel Fuel Blend Standard), the European Union (Renewable Energy Directive II), the United States (Renewable Fuel Standards), Japan (FY2030), Russia (Energy Strategy Bill 2035), India (Revised National Policy on Biofuels), and South Africa (Biofuels Regulatory Framework).

While current policies focus on bioenergy to decarbonise the energy system, some also contain provisions to minimise the potential environmental and social trade-offs from bioenergy production. For instance, the EU-REDII and US-RFS assign caps on the use of biofuels, which are associated with indirect land-use change and food-security concerns. The Netherlands has a stringent set of 36 sustainability criteria to which the certified biomass needs to comply. The EU-REDII also sets a timeline for the complete phase-out of high-risk biofuels. Furthermore, both policies stipulate that biofuels must reduce emissions compared to the fossil alternative by a specific level. While this emission accounting aims to account for direct and indirect land use change, the emission factors used may not appropriately cover the future emissions taking place during biofuel production if high demand arises after 2050 (Daioglou et al. 2020), or in the hypothetical 'what-if' scenario case in which large areas of the boreal and Amazon forest would be replaced by bioenergy plantations (Hanssen et al. 2020). The Brazilian NDC combines the promotion of biofuels with a strengthening of the forest code and promotion of low carbon agricultural policies, which offers a more direct route to producing low impact biofuels. Favero et al (2020) have shown that if bioenergy policies are efficiently combined with carbon sequestration policies, as proposed by Brazil, most carbon dense old-growth forests would be protected from conversion to biofuels, even under very high bioenergy demand scenarios.

7.6.2.3 Voluntary actions and agreements

Forest certification programs, such as Forest Sustainability Council (FSC) or Programme for the Endorsement of Forest Certification (PEFC), are consumer driven, voluntary programs that influence timber harvesting practices, and may reduce emissions from forest degradation with reduced impact logging and other approaches (*medium confidence*). Forest certification has expanded globally to over 440 Mha (Kraxner et al. 2017). As the area of land devoted to certification has increased, the amount of timber produced from certified land has increased. In 2018, FSC accounted for harvests of 427 million m^3 and jointly FSC and PEFC accounted for 689 million m^3 in 2016 or around 40% of total industrial wood production (UN FAO 2017). There is evidence that reduced impact logging can reduce carbon losses in tropical regions (Pearson et al. 2014; Ellis et al., 2014). Forest certification, however, appears to have little impact on deforestation control (Blackman et al. 2018).

Supply chain management in the food sector encourages more widespread use of conservation measures in agriculture (*high confidence*). The number of private commitments to reduce deforestation from supply chains has greatly increased in recent years, with at least 760 public commitments by 447 producers, processors, traders, manufacturers and retailers as of March 2017 (Donofrio et al. 2017). Industry partnerships with NGOs, such as the Roundtable on Sustainable Palm Oil (RSPO), have become more widespread and visible in agricultural production. For example, RSPO certifies members all along the supply chain for palm oil and claims around 19% of total production. Similar sustainability efforts exist for many of the world's major agricultural products, including soybeans, rice, sugar cane, and cattle.

There is evidence that the Amazon Soy Moratorium (ASM), an industry-NGO effort whereby large industry consumers agreed voluntarily not to purchase soybeans grown on land deforested after 2006, have had an impact on deforestation in the legal Amazon (Nepstad et al. 2014; Gibbs et al. 2015). However, remote sensing monitoring shows that the new agricultural frontier of soy is no longer in the Amazon but in the Cerrado's (Brazilian savannas) last continuous areas of native vegetation. These savannas are considered one of the global hotspots for biodiversity and have significant carbon stocks. These data challenge the Amazonian Soy Moratorium calling attention to Cerrado's conservation, which was not included in the Soy Moratorium (Lima et al. 2019). In addition, while voluntary efforts may improve environmental outcomes for a time, it is not clear that they are sufficient to deliver long-term reductions in deforestation, given the increases in deforestation that have occurred in the Amazon in recent years. Voluntary efforts would be closer to achieve global goals to slow deforestation if they present strong linkages to regulatory or other approaches (Lambin et al. 2018).

Box 7.12 Case study: Deforestation control in the Brazilian Amazon

Summary

Between 2000 and 2004, deforestation rates in the Brazilian Legal Amazon (is a socio-geographic division containing all nine Brazilian states in the Amazon basin) increased from 18,226 to 27,772 km^2 yr^{-1} 2008 (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes). A set of public policies designed in participatory process involving federal government, states, municipalities, and civil society successfully reduced deforestation rates until 2012. However, deforestation rates increased after 2013, and particularly between 2019 and 2020. Successful deforestation control policies are being negatively affected by changes in environmental governance, weak law enforcement, and polarisation of the national politics.

Background

In 2004, the Brazilian federal government started the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) (http://redd.mma.gov.br/en/legal-and-public-policy-framework/ppcdam). The PPCDAm was a benchmark for the articulation of forest conservation policies that included central and state governments, prosecutor offices, and the civil society. The decline in deforestation after 2008 is mostly attributed to these policy options. In 2012, deforestation rates decreased to 4,571 km^2 yr^{-1}.

Case description

Combating deforestation was a theme in several programs, government plans, and projects not being more restricted to the environmental agenda. This broader inclusion resulted from a long process of insertion and articulation in the government dating back to 2003 while elaborating on the Sustainable Amazon Plan. In May 2003, a historic meeting took place in an Amazonian city, with the President of the Republic, State Governors, Ministers, and various business leaders, civil institutions, and social movements. It was presented and approved the document entitled "Sustainable Amazonia - Guidelines and Priorities of the Ministry of Environment for the Sustainable Development of the Amazon Brazilian," containing several guidelines for conservation and sustainable use in the region. At the meeting, the Union and some states signed a Cooperation Agreement aiming to elaborate a plan for the Amazon, to be widely discussed with the various sectors of the regional and national society (MMA, 2013).

Interactions and limitations

The PPCDAm had three main lines of action: 1. territorial management and land use; 2. command and control; and 3. promotion of sustainable practices. During the execution of the 1st and 2nd phases of the PPCDAm (2004-2011), important results in the territorial management and land use component included, for example, the creation of 25 Mha of federal Protected Areas (PAs) located mainly in front of the expansion of deforestation, as well as the homologation of 10 Mha of Indigenous Lands. Also, states and municipalities created approximately 25 Mha, so that all spheres of government contributed to the expansion of PAs in the Brazilian Amazon. In the Command and Control component, agencies performed hundreds of inspection operations against illegal activities (e.g., illegal logging) under strategic planning based on technical and territorial priorities. Besides, there was a significant improvement of the environmental monitoring systems, involving the analysis of satellite images to guide actions on the ground. Another policy was the restriction of public credit to enterprises linked to illegal deforestation following a resolution of the Brazilian Central Bank (2008) (MMA,2013). Also, in 2008, Brazil created the Amazon Fund, a REDD+ mechanism (http://www.amazonfund.gov.br/en/home/).

However, the country's political polarisation has gradually eroded environmental governance, especially after the Brazilian Forest Code changes in 2012 (major environmental law in Brazil), the presidential impeachment in 2016, presidential elections in 2018, and the start of the new federal administration in 2019. Successful deforestation control policies are being negatively affected by critical changes in the political context, and weakening the environmental rule of law, forest conservation, and sustainable development programs (for example, changes in the Amazon Fund governance in disagreement with the main donors). In 2019, the annual deforestation rate reached 10,129 km^2 being the first time it surpassed 10,000 km2 since 2008 (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes). Besides, there has been no effective transition from the historical economic model to a sustainable one. The lack of clarity in the ownership of land is still a major unresolved issue in the Amazon.

Lessons

The reduction of deforestation in the Brazilian Amazon was possible due to effective political and institutional support for environmental conservation. The initiatives of the Action Plan included the expansion of the protected areas network (conservation unities and indigenous lands), improvement of deforestation monitoring to the enforcement of environmental laws, and the use of economic instruments, for example, by cutting off public credit for municipalities with higher deforestation rates (Nepstad et al. 2014, Souza Jr. et al. 2013, Arima et al. 2014, Ricketts et al. 2010, Blackman and Veit 2018).

The array of public policies and social engagement was a historical and legal breakthrough in global protection. However, the broader political and institutional context and actions to reduce the representation and independent control of civil society movements in decision-making bodies weaken this structure with significant increases in deforestation rates, burnings, and forest fires.

Box 7.13 Regreening the Sahel, Northern Africa

Case description

In the West African Sahel, more than 200 million trees have regenerated on more than 5 Mha of 2008 (Reij, 2009) with the epicentre of experimentation and scale up being the Maradi/Zinder region of Niger. The vast areal extent of this change generates significant carbon reduction potential, though the per unit area increase in carbon for these systems is relatively modest, about 0.4 Mg C ha^{-1} a^{-1} (Luedeling and Neufeldt, 2012). At the same time, these ‘parkland’ agroforestry systems protect soils from erosion, provide fodder for animals during dry seasons, create microclimates reducing heat stress, recharge groundwater when trees are managed at intermediate densities, generate critical nutrition and income benefits and generally act as safety nets to climate and other shocks for vulnerable rural households (Bayala *et al.*, 2014, 2015; Binam *et al.*, 2015; Ilstedt *et al.*, 2016; Chomba *et al.*, 2020).

Lessons

A mélange of factors including increased precipitation, migration, community development, economic volatility, and local policy reform have all been suggested as primary drivers of the regreening of the Sahel. While practically all agree that the cause was not singular, most point toward deregulation of the forest regulation as a critical event (Garrity and Bayala, 2020). This gave farmers greater control over the management and use of trees on their land and freedom from fear of extortion for tree management from government officers. The change had been precipitated by economic decline over at least a decade which led to greater regional autonomy combined with successful pilots and NGO-led experimentation, cash-for-work, and training efforts (Sendzimir, Reij and Magnuszewski, 2011).

Effective involvement of farmers in planning and implementation strategies ensured alignment with local practices, cultural values, community aspirations and market opportunities. Furthermore, regreening takes place when dormant seed or tree stumps sprout through the technique, called Farmer Managed Natural Regeneration (FMNR). Without planting new trees, FMNR is radically cheaper than other approaches to restoration, with estimated costs as low as 20 USD/ha (Reij and Garrity, 2016). Such low investment costs further contributed to the spontaneous replication across the landscape. Together, this mix of factors contributed to a groundswell of action that affected rights, access, and use of local resources (Tougiani, Guero and Rinaudo, 2009; Chomba *et al.*, 2020).

Regreening the Sahel and the transformation of the landscape has resulted from the actions of hundreds of thousands of individuals responding to social and biophysical signals (Hanan, 2018). This is perhaps a unique example for climate change mitigation, where eliminating regulations – versus increasing them - has led to carbon removal.

7.6.2.4 Mitigation Effectiveness: Additionality, Permanence and Leakage

Additionality, permanence and leakage have been widely discussed in the forestry and agricultural offset literature (Murray et al. 2007), including in AR5 (Section 11.3.2 of the WGIII report) and earlier assessment reports. Since the earlier assessment reports, new studies have emerged to provide new insights on the effect of these issues on offset credibility. This assessment also provides additional context not considered in earlier assessments.

Typically, carbon registries will require that project developers show additionality by illustrating that the project is not undertaken as a result of a legal requirement, and that the project achieves carbon reductions above and beyond a business as usual. The protocols developed by the California Air Resources Board to ensure permanence and additionality are strong standards and may even limit participation (e.g. Ruseva et al. 2017). The business as usual often is defined as past management actions by the same entity that can be verified. Additionality can thus be observed in the future as a difference from historical actions. This approach has been used by several countries in their UNFCCC Biennial reports to establish reductions in carbon emissions from avoided deforestation.

However, alternative statistical approaches have been deployed in the literature to assess additionality with a quasi-experimental method that rely on developing a counterfactual (e.g. Andam et al. 2008; Blackman 2015; Sills et al. 2015; Fortmann et al. 2017; Roopsind et al. 2019). In several studies, additionality in avoided deforestation was established after the project had been developed by comparing land-use change in treated plots where the policy or program was in effect with land use change in similar untreated plot. Alternatively, synthetic matching statistically compares trends in a treated region (i.e., a region with a policy) to trends in a region without the policy, and has been applied in a region in Brazil (e.g., Sills et al., 2015), and at the country level in Guyana (Roopsind et al. 2019).

While these analyses establish that many projects to reduce deforestation have overcome hurdles related to additionality (*high confidence),* there has not been a systematic assessment of the elements of project or program design that lead to high levels of additionality. Such assessment could help project developers design projects to better meet additionality criteria.

The same experimental methods have been applied to analyse additionality of the adoption of soil conservation and nutrient management practices in agriculture. Claasen et al. (2018) find that programs to promote soil conservation are around 50% additional across the US (i.e. 50% of the land enrolled in soil conservation programs would not have been enrolled if not for the program), while Woodward et al. (2016) find that little to no conservation tillage is additional. Claassen et al. (2018) also examine nutrient management programs and find that payments for nutrient management plans are nearly 100% additional, although the effects of these plans on actually reducing nutrient inputs provides for less additionality. It is not clear if the same policy approaches would also lead to additionality in other regions.

Permanence focuses on the potential for carbon sequestered in offsets to be released in the future due to natural or anthropogenic disturbances. Most offset registries have strong permanence requirements, although they vary in their specific requirements. The VCS/Verra for instance has a pool of additional carbon credits that provides a buffer against inadvertent losses. Alternatively, the Climate Action Reserve (CAR) protocol for forests requires carbon to remain on the site for 100 years. The carbon on the site will be verified at pre-determined intervals over the life of the project. If carbon is diminished on a given site, the credits for the site have the relinquished and the project developer has to use credits from their reserve fund (either other projects or purchased credits) to make up for the loss.

As shown in Van Kooten et al. (1995), if the carbon gains are fully credited when they occur, then project developers should relinquish those credits, less any permanent storage in wood products, when the carbon is lost from the site due to disturbance (harvest, fire, etc.). On the other hand, if the credits are only partially paid in any given year, e.g., they are rented, then project developers may not need to relinquish their credits see Favero et al. (2019). Most project systems to date appear to have taken the first approach, assuming that carbon gains are fully credited during the project period, so that when losses occur, the project partners are required to make up the difference. Approaches like California's, which provide full credit value in exchange for requiring 100-year permanence likely have increased costs on projects and reduced the amount of forest carbon supplied in voluntary or regulatory markets (*high confidence*).

Estimates of leakage in forestry projects in the AR5 suggest that it can range from 10% to over 90% in the United States (Murray et al., 2004), and 20-50% in the tropics (Sohngen and Brown 2004) for forest set-asides and reduced harvesting. Carbon offset protocols have made a variety of assumptions. The Climate Action Reserve (CAR) assumes it is 20% in the US. One of the voluntary protocols (Verra) uses specific information about the location of the project to calculate a location specific leakage factor.

More recent literature has developed explicit estimates of leakage based on statistical analysis of carbon projects or programs. The literature suggests that there are two economic pathways for leakage (e.g. Roopsind et al. 2019), either through a shift in output price that occurs when outputs are affected by the policy or program implementation, as described in (Gan and McCarl 2007; Murray et al. 2004b; Sohngen and Brown 2004b; Wear and Murray 2004), or through a shift in input prices and markets, such as for labor or capital, as analyzed in Alix-Garcia et al. (2012), Andam et al. (2008), Fortmann et al. (2017), Honey-Rosés et al. (2011). Estimates of leakage through product markets (e.g. timber prices) have suggested leakage of up to 90% (Sohngen and Brown 2004; Murray et al. 2004; Gan and McCarl, 2007; Kallio and Solberg 2018), while studies that consider shifts in input markets are considerably smaller. The analysis of leakage for the Guyana program by Roopsind et al. (2019) revealed no statistically significant leakage in Suriname. A key design feature for any program to reduce leakage is to encompass more area in the program. Efforts to continue to draw more forests into carbon policy initiatives will reduce leakage over time (Roopsind et al. 2019), suggesting that if NDCs continue to encompass a broader selection of policies, measures and forests over time, leakage will decline.

7.6.3 General Assessment of Current Policies and Potential Future Approaches

The Paris Agreement endorses a wide range of policy approaches, including REDD+, sustainable forest management, joint mitigation and adaptation, and emphasises the importance of non-carbon benefits and equity for sustainable development (Martius et al. 2016). Around USD 0.7 billion yr^{-1} has been invested in land-based carbon offsets (see Table 7.9), but as noted in (Streck 2012), there is a large funding gap between these efforts and the scale of efforts necessary to meet 1.5 or 2.0°C targets outlined in the Special Report on Warming of 1.5ºC. For instance, estimates suggest that forestry actions could achieve up to 5.8 $GtCO_2$ yr^{-1} in the next several decades but would cost USD 431 billion yr^{-1}. Over half of this investment is expected to occur in Latin America, with 13% in SE Asia and 17% in Sub-Saharan Africa (Austin et al. 2020). Other studies have suggested that similar sized programs are possible, although they do not quantify total costs (e.g. Griscom et al. 2017; Busch et al. 2019). The currently quantified efforts to reduce net emissions with forests and agricultural actions are helpful, but society will need to quickly ramp up investments in order to achieve carbon sequestration levels consistent with high levels of mitigation. Only 2.5% of climate mitigation funding goes to land-based mitigation options, an order of magnitude below the potential proportional contribution (Buchner et al. 2015).

To date, there has been significantly less investment in agricultural projects than forestry projects to reduce net carbon emissions (Table 7.9). For example, the technical potential for soil carbon sequestration in croplands is 0.4-6.8 $GtCO_2$ yr^{-1} (Table 7.5), however, less than 2% of the carbon in Table 7.9 is derived from soil carbon sequestration projects. While reductions in methane emissions due to enteric fermentation constitute a large share of agricultural mitigation reported in Table 7.5, agricultural methane emission reductions have been relatively modest compared to forestry sequestration. The protocols to quantify emission reductions in the agricultural sector are available and have been tested, and the main limitation appears to be the lack of available of financing or the unwillingness to re-direct current subsidies (*medium confidence*).

Although quantified emission reductions in agricultural projects is limited to date, a number of OECD and Economy in transition parties have reduced their net emissions through carbon storage in soils of croplands remaining croplands since 2000. These reductions in emissions have typically resulted from policy innovations outside of the climate space, or market trends. For example, in the United States there has been widespread adoption of conservation tillage in the last 30 years as a labour-saving crop management technique. In Europe, N_2O and CH_4 emissions have declined in agriculture due to reductions in nutrient inputs and cattle numbers (Henderson et al., 2018). These reductions may be linked to subsidies as part of the Common Agricultural Policy (see Section 7.6.2), and they could be linked to higher nutrient prices in the 2000-2014 period. Other environmental policies could play a role, for example, efforts to reduce water quality impacts of phosphorus in The Netherlands may ultimately reduce cattle numbers there, lowering CH_4 emissions.

Numerous developing countries have established policy efforts to abate agricultural emissions or increase carbon storage. Brazil, for instance, developed a subsidy program in 2010 to promote sustainable development in agriculture, and practices that would reduce GHG emissions. Henderson et al. (2020) report that this program reduced GHG emission in agricultural by up to 170 $MtCO_2$ between 2010 and 2018. However, the investments in low-carbon agriculture in Brazil amounted only 2% of the total funds for conventional agriculture in 2019 (Brasil 2019). Other programs in Brazil focused on deforestation had successes and failures, as described in Box 7.12. Indonesia has engaged in a wide range of programs in the REDD+ space, including a moratorium implemented in 2011 to prevent the conversion of primary forests and peatlands to oil palm and logging concessions (Henderson et al. 2020;

Tacconi and Muttaqin, 2019; Wijaya et al. 2017). Efforts to restore peatlands and forests have also been undertaken. Indonesia reports that results based REDD+ programs have been successful and have led to lower rates of deforestation than otherwise (Table 7.9).

Existing policies focused on GHG management in agriculture and forestry is less advanced in Africa than in Latin American and Asia, however, Henderson et al. (2020) report on 10 countries in Sub Saharan Africa that have included explicit policy proposals for reducing AFOLU GHG emissions through their NDCs. These include efforts to reduce N_2O emission, increase implementation of conservation agriculture, improve livestock management, and implement forestry and grassland practices, including agroforestry. Within several of the NDCs, countries have explicitly suggested intensification as an approach to reduce emission in the livestock sector.

The agricultural sector throughout the world is influenced by many policies that affect production practices, crop choices, and land use. It is difficult to quantify the effect of these policies on reference level carbon emissions from the sector, as well as the cost estimates presented in Sections 7.4 and 7.5. The presence of significant subsidy programs intended to improve farmer welfare and rural livelihoods makes it more difficult to implement regulatory programs aimed at reducing net carbon emissions in agriculture, however, it may increase the potential to implement new subsidy programs that encourage practices aimed at reducing net emissions (*medium confidence*). For instance, in the US, crop insurance can influence both crop choices and land use (Claasen et al. 2017; Miao et al. 2016), both of which will affect emission trends. Regulations to limit nutrient applications have not been widely considered, however, federal subsidy programs have been implemented to encourage farmers to conduct nutrient management planning.

A key factor that will influence future carbon storage in so-called natural climate solutions involves considering short- and long-term climate benefits, as well as interactions among various natural climate solution options. The benefits of various natural climate solutions depend on a variety of spatially dependent issues as well as institutional factors, including their management status (managed or unmanaged systems), their productivity, opportunity costs, technical difficulty of implementation, local willingness to consider, property rights and institutions, among other factors. Biomass energy, as described elsewhere in this chapter and in (Cross-Chapter Box Bioeconomy in Chapter 12), is a potent example of the many trade-offs that emerge when policies favour one type of mitigation strategy over another. For instance efforts to ramp up biomass energy production without considering how those policies would affect carbon stocks on the land base could cause environmental damages in natural forests, including causing biomass energy to be a net source of carbon emissions (Searchinger et al. 2009; Buchholtz et al. 2016; Khanna et al. 2017; DeCicco and Schlesinger 2018; Favero et al. 2020). It is argued that a carbon tax on only fossil fuel derived emissions, may lead to massive deployment of bioenergy and net carbon emissions may rise when implemented at massive scales of hundreds of millions of tonnes of biomass (Favero et al. 2020) if not combined with policies aiming sustainable forest management and protection of forest carbon stocks (Nabuurs et al. 2017) (*high confidence*).

If biomass energy production expands and shifts to carbon capture and storage (e.g. BECCS) during the century, there could be a significant increase in the area of crop and forestland used for biomass energy production (Section 7.4). BECCS is not projected to be used widely for a number of years, but in the meantime, policy efforts to advance natural climate solutions including reforestation and restoration activities (Strassburg et al. 2020) combined with sustainable management and provision of agricultural and wood products are widely expected to increase the terrestrial pool of carbon (Cross-Working Group Box 3). Carbon sequestration policies, sustainable land management (forest and agriculture), and biomass energy policies can be complementary (Favero et al. 2017; Baker et al. 2019). However, if private markets emerge for biomass and BECCS only on the scale suggested in the SR1.5 warming, policy efforts must ramp up to substantially value, encourage, and protect terrestrial carbon stocks to avoid outcomes inconsistent with many SDGs (*high confidence*).

7.6.4 Barriers and opportunities for AFOLU mitigation

The AR5 and other assessments have acknowledged many barriers and opportunities to effective implementation of AFOLU measures. Many of these barriers and opportunities focus on the context in developing countries, where both a significant portion of the mitigation is expected to happen, and where domestic financing for implementation is likely to be limited. This context is illustrated by the "Shared Socio-economic Pathways" (SSPs). When introduced into Integrated Assessment Models (IAMs), wide variation in mitigation potential of land-use and agricultural systems emerges across the scenarios, leading to a wide range of greenhouse gas emissions. Although more efficient food production systems and globalised trade have the potential to enhance the extent of natural ecosystems leading to lowest greenhouse gas emissions from the land system and decreasing food prices over time (Popp et al. 2017), this (or any) pathway will both create new barriers to implementation and encourage new opportunities. It is important to consider the current context in any country or region, but it is highly uncertain how that context may change in the future as well as the unknown impacts of climate change.

7.6.4.1 Socio-economic barriers and opportunities

Design and coverage of the financing mechanisms. The lack of resources thus far committed to implementing AFOLU mitigation, income and access to alternative sources of income in rural households that rely on agriculture or forests for their livelihoods remains a considerable barrier to adoption of AFOLU (*high confidence*). This was noted in the AR5, but data in Section 7.6.1 illustrates that to date only USD 0.7 billion yr^{-1} has been spent on AFOLU mitigation, well short of the more than USD 400 billion yr^{-1} that would be needed to achieve the economic potential described in Section 7.4. Despite long-term recognition that AFOLU can play an important role in mitigation, the *economic incentives* necessary to achieve AFOLU aspirations as part of the Paris Agreement or to maintain temperatures below 2.0 °C have not emerged. Without quickly ramping up spending, the lack of funding to implement projects will remain a critical barrier (*high confidence*). Investments are critically important in the livestock sector, which has the highest emissions reduction potential among options because actions in the sector influence agriculture specific activities, such as enteric fermentation, as well as deforestation (Mayberry et al. 2019). In many countries with export-oriented livestock industries, livestock farmers are the custodians of large swaths of forests or re-forestable areas. Incentive mechanisms and funding can encourage adoption of mitigation strategies however, funding is currently too low to make consistent progress.

Scale and accessibility of financing. The largest share of funding to date has been for REDD+ projects, and many of the commitments to date suggest that there will be significant funding in this area for the foreseeable future. Funding for conservation programs in OECD countries and China has shown to influence outcomes in other areas such as water quality and species protection. As noted elsewhere, considerably less has been available for agricultural projects aimed specifically at reducing carbon emissions globally, and outside of voluntary markets, there do not appear to be large sources of funding emerging either through international organisations, or national programs. In the agricultural sector the funding options have to be sought through the current subsidy programs, and either expanding those, or redirecting existing resources from non-GHG conservation to GHG measures (Henderson et al. 2020).

Risk and uncertainty. Most approaches to reduce emissions, especially in agriculture, require new or different technologies that require significant time or financial investments by the landholders who will implement them. As many agricultural operators are risk averse, adoption rates are often slow. Evidence that AFOLU measures increase returns or that individual landholders will be compensated for potential losses can improve adoption rates, but research to illustrate these financial pathways is often lacking, an exception being Hussain et al. (2013), although this knowledge reaches farmers only after long extension programmes.

Poverty. Poverty and social inequality are critical aspects of mitigation and adaptation plans given the impacts of climate change on vulnerable people and communities (IPCC, 2014). In the NDCs, 82 Parties included references to social issues (e.g. poverty, inequality, human well-being, marginalisation) being poverty the most considered factor (70 Parties). The number of hungry people in the world is growing, reaching 821 million in 2017 or one in every nine people (FAO et al. 2018) but two-thirds of people who are hungry live in rural areas (Laborde et al. 2020). For mitigation strategies in the land sector, the consideration of rural poverty and food insecurity is central as among around 570 million farms in the world, more than 475 million are smaller than 2 hectares. Mitigation policies may benefit the poor or worsen poverty. It is important to evaluate how mitigation policies affect the poor in developing countries and the potential trade-offs between the positive and negative impacts on poverty alleviation (Barbier, 2014; Hussain et al. 2013).

Cultural values and social acceptance. Barriers to adoption of mitigation techniques and methods will be strongest where historical practices represent long-standing traditions (*high confidence*). Adoption of new mitigation practices, however, may proceed quickly if the technologies can be shown to improve crop yields, reduce costs, or otherwise improve livelihood prospects (Ranjan et al. 2019; Mullimgi et al. 2019). In the AR6, new estimates of the potential for shifts in diets and reductions in food waste have highlighted these mitigation activities, but given long-standing dietary traditions within most cultures, some of the strongest barriers exist for efforts to change diets (*medium confidence*). Furthermore, changing diets may be feasible to the top 20-30% of the well fed, but the billions undernourished will need more food and more meat. Regulatory or tax approaches will face strong resistance, while efforts to use educational approaches and voluntary measures have limited potential to slow changes in consumption patterns due to free-riders, rebound effects, and other limitations. Efforts to reduce food waste face similar barriers in developed countries where most of the food waste occurs after consumers have purchased food (FAO 2019). Food waste in developing countries is greatest at the production stage, i.e. in fields at harvest, and there are opportunities to align reductions in food waste with improved production efficiency (FAO 2019). However, this will require new production methods, technologies, investment, and potentially labour, which presents an important barrier to implementation of food waste reduction in developing country agricultural systems. (FAO 2019).

7.6.4.2 Institutional barriers and opportunities

Transparent and accountable governance. Good governance and accountability are crucial for the implementation of forest and agriculture mitigation options. Implementation of the Paris Agreement will require large-scale estimation, modelling, monitoring, reporting and verification of GHG inventories, mitigation actions and their implications and co-benefits, along with reporting on climate change impacts and adaptation. Furthermore, given that many projects have been developed and compensated, efforts must be made to integrate the accounting from projects to the country level. While global datasets have emerged to measure forest loss, at least temporarily (e.g. Hansen et al. 2013), similar datasets do not exist for forest degradation and agricultural carbon stocks or fluxes. Most developing countries have insufficient capacity to address research needs, modelling, monitoring, reporting and data requirements (e.g. Ravindranath et al. 2017 for India) compromising transparency, accuracy, completeness, consistency and comparability. In spite of the many synergies between climate policy instruments and biodiversity conservation, current policies often fall short of realising this potential (Essl et al. 2018).

Opportunity for political participation of local stakeholders is also a critical factor because in many nations with the highest deforestation rates, forest ownership rights often are not sufficiently documented and secured (Essl et al. 2018). Since incentives for self-enforcement can have an important influence on deforestation rates (Fortmann et al, 2017), weak governance and insecure property rights are significant barriers to introduction of forest carbon offset projects in developing countries, where many of the low-cost options for such projects exist (Gren and Zeleke 2016).

Clear land tenure and land-use rights. Unclear property rights and tenure insecurity undermine the incentives to improve productivity, lead to food insecurity, undermine REDD+ objectives, discourage tree planting and forest management, and result in conflict between different land users (Sunderlin et al. 2018; Antwi-Agyei et al. 2015; Borras and Franco 2018; Felker et al. 2017; Riggs et al. 2018; Kansanga and Luginaah 2019). Although over 500 million hectares of forests have been converted to community management with clear property rights in the past two decades (RRI, 2018), this barrier will limit adoption of forest and agricultural mitigation practices on a considerable area (Gupta et al. 2016). Governance challenges exist at all levels of government, with poor coordination, insufficient information sharing, and concerns over accountability playing a prominent role within REDD+ projects and programs (Ravikumar et al. 2015). In some cases, governments are increasingly centralising REDD+ governance and limiting the distribution of governance functions between state and non-state actors (Zelli et al. 2017; Phelps et al. 2010). FLEGT and REDD+ governance regimes are in some cases acting with overlaps and duplication, which may limit governance effectiveness (Gupta et al. 2016).

Lack of institutional capacity. Institutional complexity represents a major challenge in integrating mitigation measures in agriculture, forest and other land uses (Bäckstrand et al. 2017). Current institutional practices in implementing adaptation and mitigation projects and programs are limited to seeking co-benefits, which are necessary but insufficient steps towards promoting synergies at landscape scale (Duguma et al. 2014). Another aspect of institutional complexity is the different biophysical and socio-economic circumstances as well as the public and private financial means involved in the architecture and implementation of REDD+ and other initiatives (Zelli et al. 2017).

7.6.4.3 Ecological barriers and opportunities

Availability of land and water. Climate mitigation scenarios in the two recent special reports (SR1.5C and SRLCC) that aim to limit global temperature increase to 2°C or less involve negative emissions. To support large-scale carbon dioxide (CO_2) removal from the atmosphere, these scenarios involve significant land-use change, due to afforestation/reforestation, avoided deforestation, and deployment of Biomass Energy with Carbon Capture and Storage (BECCS). While a considerable amount of land is certainly available for new forests or new bioenergy crops, that land has current uses that will affect not only the costs, but also the willingness of current users or owners, to shift uses. Regions with private property rights and a history of market-based transactions may be the most feasible for land use change or land management change to occur. Areas with less secure tenure or a land market with fewer transactions in general will likely face important hurdles that limit the feasibility of implementing novel nature-based solutions.

Implementation of nature-based solution may have local or regionally important consequences for other ecosystem services, some of which may be negative (*high confidence*). For instance, afforestation can have minor to severe consequences for surface water acidification, depending on site-specific factors and exposure to air pollution and sea-salts (Futter et al. 2019). Afforestation may also reduce runoff due to increased root uptake and higher evapotranspiration. Afforestation will increase average deposition rates slightly due more effective atmospheric scavenging of dry deposition. The potential effects of coastal afforestation on sea-salt related acidification could lead to re-acidification and damage on aquatic biota (Milkovic et al. 2019; Azarnivand et al. 2020).

Specific soil conditions, water availability, GHG emission-reduction potential as well as natural variability and resilience. Recent analysis by Cook-Patton et al. (2020) illustrates large variability in potential rates of carbon accumulation for afforestation and reforestation options, both within biomes/ecozones and across them. Their results suggest that while there is large potential for afforestation and reforestation, the carbon uptake potential in land-based climate change mitigation efforts is highly dependent on the assumptions related to climate drivers, land use and land management, and soil carbon responses to land-use change. Less analysis has been conducted on bioenergy crop yields, however, bioenergy crop yields are also likely to be highly uncertain, suggesting that bioenergy supply could exceed or fall short of expectations in a given region, depending on site conditions.

Most climate mitigation scenarios involve negative emissions, especially those that aim to limit global temperature increase to 2°C or less. However, the carbon uptake potential in land-based climate change mitigation efforts is highly uncertain depending on the assumptions related to land use and land management in the models including model assumptions regarding bioenergy crop yields and simulation of soil carbon response to land-use change. Differences between land-use models and DGVMs regarding forest biomass and the rate of forest regrowth also have an impact, albeit smaller, on the results (Krause et al. 2017). The efficiency of AFOLU mitigation potential will be influenced by the effects of climate change on natural and managed ecosystems, including changes in crop yields, shifts in terrestrial ecosystem productivity, vegetation migration, wildfires and other disturbances. For instance, if climate change reduces crop yields, increases crop and livestock prices, and increases pressure on undisturbed forest land for food production (e.g. Nelson et al. 2014), new barriers for implementation of most agricultural mitigation technologies will arise (*medium confidence*). Costs to implement many forestry options also will increase (*high confidence*).

It is suggested that climate change will lead to an increase in carbon stocks of most forests around the world, with the greatest gains in tropical forest regions (Kim et al. 2017). Temperate forest regions also were projected to see strong increases in productivity, but these gains were partially offset by carbon loss to fire in the boreal zone. The drivers of forest changes varied regionally, associated with differing mechanisms as expansion or contraction of forests, with further loss of area to wildfire; and changes in vegetation productivity. These results contrast with previous studies that pointed to the likelihood of reduced forest carbon stocks due to climate feedback, even with CO_2 fertilisation (Cox et al. 2013; Friedlingstein 2015). Nonetheless, climate change is expected to present a formidable challenge to implementation of nature-based solutions beyond 2030 (*high confidence*).

The observed increase in the terrestrial sink over the past half century might to be linked to changes in the global environment, such as increased atmospheric CO_2 concentrations, N deposition, or changes in climate (Ballantyne et al. 2012; O´Sullivan et al. 2019). It is uncertain if this large terrestrial carbon sink will continue in the future (e.g. Aragão et al. 2018). For instance, negative synergies between local impacts like deforestation and forest fires may interact with global drivers like climate change and lead to tipping points (Lovejoy and Nobre 2018). While the terrestrial sink relies on regrowth on secondary forests (Houghton and Nassikas 2017), there is emerging evidence that the sink will slow in the northern hemisphere as these forests age (Nabuurs et al. 2013; Coulston et al. 2015), although saturation may take decades (Zhu et al. 2018). Forest management through replanting, variety selection, fertilisation, and other management techniques, has increased the terrestrial carbon sink over the last century (Sohngen and Mendelsohn 2019), and the future sink potential may be sufficiently robust to the impacts of climate change (Tian et al. 2018).

The mitigation potential of land-based negative emissions technologies (NETs) is constrained by critical social objectives and ecological limits. Three types of risks were identified in relation to NETs: (1) that NETs will not ultimately prove feasible; (2) that their large-scale deployment involves unacceptable ecological and social impacts; and (3) that NETs prove less effective than hoped, due to irreversible climate impacts, or reversal of stored carbon (Dooley and Kartha 2018). Further, forest conversion to bioenergy crops could cause net losses of carbon from the land (Harper et al. 2018). While deployment of BECCS and forest-based mitigation can be complementary (Favero et al. 2017; Baker et al. 2019), use of inefficient policy approaches could lead to net carbon emissions if BECCS replaces high-carbon content ecosystems with crops.

Adaptation benefits. Biodiversity may improve resilience to climate change impacts as more-diverse systems could be more resilient to climate change impacts, thereby maintaining ecosystem function and preserving biodiversity (Hisano et al. 2018). However, losses in ecosystem functions due species shifts or reductions in diversity may impair the positive effects of biodiversity on ecosystems. Forest management strategies based on biodiversity and ecosystems functioning interactions can augment the effectiveness of forests in reducing climate change impacts on ecosystem functioning (*high confidence*). In spite of the many synergies between climate policy instruments and biodiversity conservation, current policies often fall short of realising this potential (Essl et al. 2018).

7.6.4.4 Technological barriers and opportunities

Monitoring, reporting, and verification. Development of satellite technologies to assess potential deforestation has grown in recent years with the release of 30 m data by Hansen et al. (2013), however, it is important to recognise that this data only captures tree cover loss and with increasing accuracy over time cautioning the use of these data (Ceccherini et al. 2020; Palahi et al. 2021). These losses could be due to many different factors, including natural disturbances like fires and traditional timber harvests in regions where forest management is significant. Furthermore, these datasets are less well developed for reforestation and afforestation. As Mitchell et al. (2017) point out, there has been significant improvement in the ability to measure changes in tree and carbon density on sites using satellite data, but these techniques are still evolving and improving. They are not yet available for widespread use globally.

Ground-based forest inventory measurements have been developed for the US with the US Forest Service Inventory and Analysis database, which is freely available to anyone in the world online (see https://www.fia.fs.fed.us/). These data are collected on plots that are measured every 5-10 years. Canada similarly provided significant information online (https://nfi.nfis.org/en). Many European countries provide data from their forest inventories, but the online resources there are less well developed. Similarly, Russia and China have not provided forest inventory data online. Other countries like Mexico, Japan, Korea, Malaysia, Australia, Guatemala, Honduras, Costa Rica, New Zealand have good inventories, but not available online either. Also, training and capacity building is going on in many developing countries under UNREDD and FAO programmes. Additional efforts to make forest inventory data available to the scientific community would improve confidence in forest statistics, and changes in forest statistics over time. To some extent the Global Forest Biodiversity Initiative fills in this data gap (https://gfbi.udl.cat/).

7.6.5 Linkages to ecosystem services, human well-being and adaptation (incl. SDGs)

The inextricable linkage between biodiversity, ecosystem services, human well-being and sustainable development is widely acknowledged (Millennium Ecosystem Assessment 2005; UN Environment 2019). Loss of biodiversity and ecosystem services will have an adverse impact on quality of life, human well-being and sustainable development (Díaz et al. 2019). Such losses will not only affect current economic growth but also impede the capacity for future economic growth.

Population growth, economic development, urbanisation, technology, climate change global trade and consumption, policy and governance are identified as key drivers of global environmental change over recent decades (Kram et al. 2014; UN Environment 2019; WWF 2020). Changes in biodiversity and ecosystem services are mainly driven by habitat loss, climate change, invasive or introduced species, over-exploitation of natural resources, and pollution (Millennium Ecosystem Assessment 2005). The relative importance of these drivers varies across biomes, regions, and countries. Climate change is expected to be a major driver of biodiversity loss in the coming decades, followed by commercial forestry and bioenergy production (OECD 2012; UN Environment 2019; Díaz et al. 2019). Population growth, in combination with rising incomes and the resulting changes in consumption and dietary patterns, will continue to exert immense pressure on land and other natural resources (Shukla et al. 2019). Current estimates suggest that 75% of the land surface has been significantly anthropogenically altered, with 66% of the ocean area is experiencing increasing cumulative impacts and over 85% of wetland area lost (Díaz et al. 2019). As highlighted in section 7.3, land-use change is driven amongst other things, by agriculture, forestry (logging and fuelwood harvesting), infrastructural development and urbanisation, all of which may also generate localised air, water and soil pollution (Díaz et al. 2019). Over a third of the world's land surface and nearly three-quarters of available freshwater resources are devoted to crop or livestock production (Díaz et al. 2019). Despite a slight reduction in global agricultural area since 2000 (FAO, 2020J1), regional agricultural area expansion has occurred, specifically in Latin America and the Caribbean, and Africa and the Middle East. Latin America and the Caribbean showed an increase in both grassland and cropland area, with this trend expected to continue (OECD-FAO 2019). The continued fragmentation and decline of tropical forests and biodiversity hotspots, endangers habitat for many threatened and endemic species, and reduces valuable ecosystem services. However, trends vary considerably by region. As reported in section 7.3, global forest area is estimated to have declined by roughly 178 Mha between 1990 and 2020 (FAO 2020), though the rate of net forest loss has decreased over the period, as a result of reduced deforestation in some countries and forest gains in others. For example, between 1990 to 2015, forest cover fell by almost 13% in the South East, largely due to an increase in timber extraction, large-scale biofuel plantations and expansion of intensive agriculture and shrimp farms (Karki et al. 2018). Over same period forest cover in North East Asia and South Asia increased by 23% and 6% respectively, through policies and instruments such as joint forest management, payment for ecosystem services, and the restoration of degraded forests (Karki et al. 2018). The increasing trend of mining in forest and coastal areas, and in river basins for extracting has had significant negative impacts on biodiversity, air and water quality, water distribution, and on human health (Section 7.3). Freshwater ecosystems equally face a series of combined threats including from land-use change, iwater extraction, exploitation, pollution, climate change and invasive species (Diaz et al. 2019).

7.6.5.1 Ecosystem Services

An evaluation of eighteen ecosystem services over the past five decades (1970-2019) found only four (agricultural production, fish harvest, bioenergy production and harvest of materials) to demonstrate increased performance, while the remaining fourteen, mostly concerning regulating and non-material contributions, were found to be in decline (Díaz et al. 2019). The value of global agricultural output (over USD 3.7 trillion in 2016) had increased approximately threefold since 1970, and roundwood production (industrial roundwood and fuelwood) by 27%, between 1980 to 2018, reaching some 4 billion m^3 in 2018. However, the positive trends in these four ecosystem services does not indicate long-term sustainability. If increases in agricultural production are realised through forest clearance or through increasing energy-intensive inputs, gains are likely to be unsustainable in the long run. Similarly, an increase in fish production may involve overfishing, leading to local species declines which also impacts fish prices, fishing revenues, and the well-being of coastal and fishing communities (Sumaila and Lam 2020). Climate change and other drivers are likely to affect fish catch potential in the future, although impacts will differ across regions (Sumaila et al. 2017).

The increasing trend in aquaculture production especially in South and South East Asia through intensive methods affects existing food production and ecosystems by diverting rice fields or mangroves (Bhattacharya and Ninan 2011). Bioenergy production may have high opportunity costs and compete with other land uses especially food production which threatens food security and affects the poor and vulnerable. But these impacts will depend on local contexts and other factors. Only a small fraction of the wood harvested is obtained from sustainably managed forests. According to the Forest Stewardship Council (FSC) only 11.3% of global roundwood production (including industrial roundwood and fuel wood) in 2016 was obtained from FSC certified forests which constitutes only 17% of the world's production forests (FSC 2018). Regulating contributions, such as soil organic carbon and pollinator diversity, have declined, indicating that gains in material contributions are often not sustainable.

Currently, land degradation is estimated to have reduced productivity in 23% of the global terrestrial area, and between USD 235 billion and USD 577 billion in annual global crop output is at risk because of pollinator loss (Díaz et al. 2019). The global trends reviewed above are based on data from 2,000 studies. It is not clear whether the assessment included a quality control check of the studies evaluated and suffer from aggregation bias. For instance, a recent meta-analysis of global forest valuation studies noted that quite a number of the studies reviewed had shortcomings such as failing to clearly mention the methodology and prices used to value the forest ecosystem services, double counting, data errors, etc, (Ninan and Inoue 2013a). Added to that the criticisms levelled against the paper by Costanza et al. (1997), such as ignoring ecological feedbacks and non-linearities that are central to the processes that link all species to each other and their habitats, ignoring substitution effects may also apply to the global assessment (Smith 1997; Bockstael et al. 2000; Loomis et al. 2000). Land degradation has had a pronounced impact on ecosystem functions worldwide (Scholes et al. 2018). Net primary productivity of ecosystem biomass and of agriculture is presently lower than it would have been under natural state on 23% of the global terrestrial area, amounting to a 5% reduction in total global net primary productivity (Scholes et al. 2018). Over the past two centuries, soil organic carbon, an indicator of soil health, has seen an estimated 8% loss globally (176 GtC) from land conversion and unsustainable land management practices (Scholes et al. 2018). Projections to 2050 predict further losses of 36 Gt C from soils, particularly in Sub-Saharan Africa. These future losses are projected to come from the expansion of agricultural land into natural areas (16 Gt C), degradation due to inappropriate land management (11 Gt C) and the draining and burning of peatlands (9 Gt C) and melting of permafrost (Scholes et al. 2018). Trends in biodiversity measured by the global living planet index covering the period 1970 to 2016 indicate a 68% decline in monitored population of mammals, birds, amphibians, reptiles, and fish (WWF 2020). The FAO's recent report on the state of the world's biodiversity for food and agriculture points to an alarming decline in biodiversity for food and agriculture including associated biodiversity such as pollination services, micro-organisms, etc. which are essential for production systems (FAO 2019b). If this is accepted as a measure of ecosystem health it shows that overall ecosystem health is consistently declining which has adverse implications for good quality of life, human well-being, and sustainable development.

Although numerous studies have estimated the value of ecosystem services over a cross section of sites, ecosystems, and regions, most of these studies evaluate ecosystem services at a single point in time (See for example, Costanza et al. 1997; Xie and Tisdell 2001; Nahuelhual et al. 2007; de Groot et al. 2012; Ninan and Inoue, 2013b; Ninan and Kontoleon, 2016). Few studies have assessed trends in the value of ecosystem services provided by different ecosystems across regions and countries. According to Costanza et al. (2014), between 1997 to 2011 the loss of global ecosystem services due to land use change is valued at between USD 4.2-20.2 trillion yr^{-1} (in 2007 USD) depending on which unit value one adopts. Over this period losses in ecosystem services values account for about 30% of the losses from land cover changes (Costanza et al. 2014). Using four alternate land use and management scenarios i.e. the Great Transition Initiative (GTI) scenarios ranging from Fortress World (BAU) to GTI (conservation) scenarios up to the year 2050, Kubiszewski et al. (2017) note that the global value of ecosystem services across these scenarios can decline by USD 51 trillion per year or increase by USD 30 trillion yr^{-1} (in 2007 USD). For global terrestrial ecosystems, the annual flow of ecosystem services values across these four alternate scenarios ranged from a decline of -46% to an increase of up to 25% when compared to the 2011 ecosystem services value of USD 7.20 trillion yr^{-1}. While these scenarios differ from the SSPs used by IAMs in this chapter, the GTI scenarios illustrate the critical importance of conducting broad based ecosystem services analysis, given how sensitive ecosystem services and their values are to changes in land use.

Climate change is a direct driver that increasingly exacerbates the impact of other drivers on human and natural systems. Land use change is a major driver behind loss of biodiversity and ecosystem services in Africa, America, Asia-Pacific, Europe and Central Asia regions (Archer et al. 2012; Rice et al. 2018; Karki et al. 2018; Fischer et al. 2018). Unsustainable extension and intensification of agriculture and forestry in many regions of the world is putting immense stress on biodiversity and ecosystem services resulting in their degradation. Projected impacts of land use change and climate change on biodiversity and ecosystem services (material and regulating contributions to people) between 2015 to 2050 are seen to have relatively less negative impacts under global sustainability scenario as compared to regional competition and economic optimism scenarios (Figure 7.19) (Díaz et al. 2019). However, these scenarios don't cover transformative changes. Small island states which are noteworthy for their marine and coastal ecosystems that provide many ecosystem services have not received due attention even though they are most vulnerable to climate change and extreme weather events The projected impacts in the Figure 7.19 are based on a subset of Shared Socioeconomic Pathway (SSP) scenarios and greenhouse gas emissions trajectories (RCP) developed in support of IPCC assessments.

7.6.5.2 Ecosystem services and mitigation options

An ecosystem-based approach is recommended to address the risks posed by climate change and extreme weather events and has several co-benefits (SCBD 2009). It involves building resilience through green solutions such as afforestation or reforestation to capture carbon, conserving or restoring mangroves to manage coastal flooding and storm surges, maintaining and increasing tree cover to reduce heat stress in cities and towns, promoting agroforestry in drought-prone areas, etc. (SCBD 2009; Royal Society 2014; Ninan and Inoue 2017). For instance conservation of mangroves can help conserve above and below ground carbon stocks, protect against storm surges, sea level rise and coastal inundation and has several co-benefits such as providing income and employment opportunities for fisheries and prawn cultivation, and conserve species that live or depend on mangroves (SCBD 2009). However, there could be synergies, trade-offs and co-benefits between ecosystem services and mitigation options. Different mitigation options have different impacts on ecosystem services although these will differ across space and contexts. A study by Nunez et al. (2020) tried to assess how 20 different land-based mitigation pathways that comply with the Paris agreement will impact on biodiversity and noted that while avoiding deforestation, reforestation of cultivated and managed areas and restoration of wetlands will deliver the largest biodiversity benefits in terms of mean species abundance (MSA), afforestation or reduced deforestation can have positive or negative impacts on MSA. Although afforestation can help carbon sequestration and making productive use of degraded lands, cultivation of monocultures such as eucalyptus will be detrimental to biodiversity, food security and water availability (Duguma et al. 2014: Bryan et al. 2015; Frank et al. 2017: Nunez et al. 2020). Afforestation may have high opportunity costs due to the large requirements of land for implementing afforestation projects. A mitigation pathway that limits temperature rise to 1.5ºC will result in an average global food calories loss of between 110-285 kcal per capita per day with a potential increase of 80-300 million undernourished people by the year 2050 if mitigation policies are driven by cost efficiency concerns (Frank et al. 2017). Many climate mitigation pathways that seek to limit global warming to 1.5ºC or 2ºC assign an important role to bioenergy crops (Hanssen et al. 2020). However, although bioenergy crops can help in carbon sequestration and reduce fossil fuel use, they can have adverse impacts on food security and biodiversity especially in areas where land is a constraint and competes with food crops (Hanssen et al. 2020). Negative impacts on biodiversity were projected also in the context of future bioenergy demand in the EU further highlighting the potential leakage effects (Di Fulvio et al. 2019) Policies to minimise trade-offs between climate stabilisation and food security goals is quite challenging and need to take note of local contexts, livelihood issues and policy priorities (Obersteiner et al. 2016; Hasegawa et al. 2018). Sustainable use and management of land and other natural resources, restoration of degraded lands, landscape-based conservation planning, reducing food wastage and changing dietary patterns towards diets with low carbon footprint can help to reverse biodiversity losses by the mid-21st century (Leclère et al. 2020). Measures such as conservation agriculture, agroforestry, soil and water conservation, afforestation, adoption of silvopastoral systems, can help to minimise trade-offs between mitigations options and ecosystem services (Duguma et al. 2014). Climate smart agriculture is being promoted to enable farmers to make agriculture more sustainable and adapt to and mitigate the adverse impacts of climate change. However, experience with climate smart agriculture in Africa has not been encouraging. For instance, a study of climate smart cocoa production in Ghana shows that due to institutional constraints such as the lack of tenure (tree) rights, bureaucratic and legal hurdles in registering trees in cocoa farms, and other barriers small cocoa producers could not realise the project benefits (Box 7.14). Experience of climate smart agriculture in some other Sub-Saharan African countries too has been below expectations (Arakelyan et al. 2017).

Box 7.14 Case study: climate smart cocoa production in Ghana

Policy Objectives

1. To promote sustainable intensification of cocoa production and enhance the adaptive capacity of small cocoa producers.
2. To reduce cocoa-induced deforestation and GHG emissions.
3. To improve productivity, incomes, and livelihoods of smallholder cocoa producers.

Policy Mix

The climate smart cocoa (CSC) production programme in Ghana involved distributing shade tree seedlings that can protect cocoa plants from heat and water stress, enhance soil organic matter and water holding capacity of soils, and provide other assistance with agroforestry, giving access to extension services such as agronomic information and agro-chemical inputs. The shade tree seedlings were distributed by NGOs, government extension agencies, and the private sector free of charge or at subsidised prices and was expected to reduce pressure on forests for growing cocoa plants. The CSC programme was mainly targeted at small farmers who constitute about 80% of the total farm holdings in Ghana. Although the government extension agency (Cocobod) undertook mass spraying or mass pruning of cocoa farms they found it difficult to access the 800,000 cocoa smallholders spread across the tropical south of the country. The project brought all stakeholders together i.e. the government, private sector, local farmers and civil society or NGOs to facilitate the sustainable intensification of cocoa production in Ghana. Creation of a community-based governance structure was expected to promote benefit sharing, forest conservation, adaptation to climate change, and enhanced livelihood opportunities.

Governance Context

Critical enablers

The role assigned to local government mechanisms such as Ghana's Community Resource Management Area Mechanisms (CREMAs) was expected to give a voice to smallholders who are an important stakeholder in Ghana's cocoa sector. CREMAs are inclusive because authority and ownership of natural resources are devolved to local communities who can thus have a voice in influencing CSC policy thereby ensuring equity and adapting CSC to local contexts. However, ensuring the long-term sustainability of CREMAs will help to make them a reliable mechanism for farmers to voice their concerns and aspirations, and ensure their independence as a legitimate governance structure in the long run. The private sector was assigned an important role to popularise climate smart cocoa production in Ghana. However, whether this will work to the advantage of smallholder cocoa producers needs to be seen.

Critical barriers

The policy intervention overlooks the institutional constraints characteristic of the cocoa sector in Ghana where small farmers are dominant and have skewed access to resources and markets. Lack of secure tenure (tree rights) where the ownership of shade trees and timber vests with the state, bureaucratic and legal hurdles to register trees in their cocoa farms are major constraints that impede realisation of the expected benefits of the CSC programme. This is a great disincentive for small cocoa producers to implement CSC initiatives and nurture the shade tree seedlings and undertake land improvement measures. The state marketing board has the monopoly in buying and marketing of cocoa beans including exports which impeded CREMAs or farming communities from directly selling their produce to MNCs and traders. However, many MNCs have been involved in setting up of CREMA or similar structures, extending premium prices and non-monetary benefits (access to credit, shade tree seedlings, agro-chemicals) thus indirectly securing their cocoa supply chains. A biased ecological discourse about the benefits of climate smart agriculture and sustainable intensive narrative, complexities regarding the optimal shade levels for growing cocoa, and dependence on agro-chemicals are issues that affect the success and sustainability of the project intervention. Dominance of private sector players especially MNCs in the sector may be detrimental to the interests of smallholder cocoa producers.

Source: Nasser et al. (2020)

7.6.5.3 Human well-being and Sustainable Development Goals

Conservation of biodiversity and ecosystem services is part of the larger objective of building climate resilience and promoting good quality of life, human well-being and sustainable development. While two of the seventeen Sustainable Development Goals (SDGs) are directly related to nature (i.e. SDGs 14 and 15 covering marine and terrestrial ecosystems and biodiversity), most of the other SDGs relating to poverty, hunger, equality, health and well-being, clean sanitation, water and energy, sustainable cities and communities, and climate action are directly or indirectly linked to nature (Blicharska et al. 2019). A survey among experts to assess how 16 ecosystem services could help in achieving the SDGs relating to good environment and human well-being suggested that ecosystem services could contribute to achieving about 41 targets across 12 SDGs (Wood et al. 2018). They also indicated cross-target interactions and synergetic outcomes across many SDGs. Poor and marginalised people, and indigenous communities depend on natural resources for their lives and livelihoods and hence conservation of biodiversity and ecosystem services is critical to sustaining their livelihoods and well-being. Nature provides a broad array of goods and services such as food, fuel, fibre, fodder, medicines, clean air and water (by regulating and reducing air and water pollutants), clean energy, incomes and employment, and many other benefits that are critical to good quality of life and human well-being. Nature can play an important role in reducing vulnerability and building resilience to disasters and extreme weather events (SCBD 2009; Royal Society 2014; Ninan and Inoue 2017).

Current negative trends in biodiversity and ecosystem services will undermine progress towards achieving 80% (35 out of 44) of the assessed targets of SDGs related to poverty, hunger, health, water, cities, climate, oceans and land (Díaz et al. 2019). The SDGs for poverty, health, water and food security and sustainability targets are closely linked through the impacts of multiple direct drivers, including climate change, on biodiversity and ecosystem functions and nature's contributions to people and good quality of life (Díaz et al. 2019). However Reyers and Selig (2020) note that the assessment by Diaz et al. 2019 could only assess the consequences of trends in biodiversity and ecosystem services for 35 out of the 150 SDG targets due to data and knowledge gaps, and lack of clarity about the relationship between biodiversity, ecosystem services and SDGs. Progress in achieving the 20 Aichi Biodiversity targets which are critical for realising the SDGs has been poor with most of the targets not being achieved or only partially realised although there is some progress in a few countries (SCBD 2020). There could be synergies and trade-offs between ecosystem services and human well-being. For instance, a study notes that although policy interventions and incentives to enhance supply of provisioning services (e.g. agricultural production) have led to higher GDP, it may have an adverse effect on the regulatory services of ecosystems (Kirchner et al. 2015). However, we are aware of the inadequacies of traditional GDP as an indicator of well-being. An increase in the benefits derived from ecosystems does not imply that gains will be shared equally due to skewed access to resources and markets, lack of technical knowledge and capacity, user conflicts, etc. (Wieland et al. 2016). For instance, a study of shellfish harvesters in Vancouver, Canada noted that access and other barriers resulted in benefits of enhanced shellfish harvesting being disproportionately shared by shellfish-dependent communities (Wieland et al. 2016). In a post-2020 global biodiversity framework, greater emphasis on the interactions between Sustainable Development Goal targets may provide a way forward for achieving multiple targets, as synergies (and trade-offs) can be considered (Díaz et al. 2019). Targets for human development and for nature need to be explicitly linked and account for socio-ecological feedbacks and multi-scale processes (Kok et al. 2017; Rosa et al. 2017; Reyers and Selig 2020). To assess nature's role and contributions to the SDGs there is a need to develop new output indicators that link with the metrics tracked by the SDG framework (Ferrier et al. 2016; Wood et al. 2018). Reyers and Selig (2020) suggest that due to the interdependencies between biodiversity, ecosystem services and sustainable development we should transit from having separate social and ecological indicators in the SDGs to social-ecological indicators. The downturn in the global economy and many national economies due to the Covid-19 pandemic may have jeopardised achieving some SDGs, notably those relating to poverty, hunger, health and equality.

7.6.5.4 Land-based Mitigation and Adaptation

Land-based mitigation and adaptation to the risks posed by climate change and extreme weather events can have several co-benefits as well as help promote development and conservation goals. The conservation of biodiversity and ecosystems enhances adaptive capacity, strengthens resilience and reduces vulnerability to climate change, thus contributing to sustainable development (Archer et al. 2012). Land-based mitigation and adaptation will not only help in reducing greenhouse gas emissions in the AFOLU sector but also help augment its role as a carbon sink by increasing the forest and tree cover through afforestation and agroforestry activities and other nature-based solutions. Land acts as a natural carbon sink with carbon stored in the soil and above ground biomass (forests and plants) (Keramidas et al. 2018). In the central 2°C scenario, improved management of land and more efficient forest practices, in the form of a drastic reduction of deforestation and an increased effort in afforestation, would account for 10% of the total mitigation effort over 2015–2050 (Keramidas et al. 2018). If managed and regulated appropriately, the Land Use, Land Use Change and Forestry (LULUCF) sector could become carbon-neutral as early as 2020–2030, being a key sector for emissions reductions beyond 2025 (Keramidas et al. 2018). Nature-based solutions with safeguards are estimated to provide 37% of climate change mitigation until 2030 needed to meet 2°C goals with likely co-benefits for biodiversity (Díaz et al. 2019). However, the large-scale deployment of intensive bioenergy plantations, including monocultures, replacing natural forests and subsistence farmlands, will likely have negative impacts on biodiversity and can threaten food and water security as well as local livelihoods, including by intensifying social conflicts (Díaz et al. 2019). Land-based mitigation and adaptation can also help improve incomes and employment and benefit the poor and vulnerable sections. The report of the Global Commission on Adaptation (2019) notes that investing USD 1.8 trillion between 2020 to 2030 in five areas namely, early warning systems, climate-resilient infrastructure, dryland agriculture crop production, global mangrove conservation and investing in making water resources more resilient can generate net benefits of USD 7.1 trillion, i.e. a benefit-cost ratio of over 3.9 (Global Commission on Adaptation 2019). The report further states that without adaptation, climate change may depress global agricultural yields by up to 30% by 2050 and the 500 million small farmers around the world will be most affected. The report also notes that climate change may push more than 100 million people in developing countries to below the poverty line by 2030. Among adaptation measures, access to crop insurance can be effective in insuring the poor and vulnerable farmers from the risks posed by climate change and extreme weather events (Panda et al. 2013). A recent study notes that in the absence of adaptation efforts climate change will not only have an adverse impact on agricultural yields in India but also aggravate the extent, depth and intensity of rural poverty in India as measured through the headcount ratio, poverty gap index and squared poverty gap index (Ninan 2019).

Land degradation has had an adverse impact on ecosystem services. According to Sutton et al. (2016) the loss in ecosystem services values due to land degradation is estimated at USD 6.3 trillion yr^{-1} which is about 10% of global GDP. Avoiding, reducing and reversing land degradation can contribute substantially to the mitigation of climate change, but land-based climate mitigation strategies must be implemented with care if unintended negative impacts on biodiversity and ecosystem services are to be avoided (Scholes et al. 2018). Between 2000 and 2009, land degradation was responsible for annual global emissions of 3.6–4.4 billion tonnes of CO_2 (Scholes et al. 2018). This is mainly due to loss and degradation of forests, the drying and burning of peatlands, and decline in the soil carbon content due to excessive disturbance and insufficient return of organic matter to the soil (Scholes et al. 2018). Land degradation will also weaken the potential of land as a carbon sink (Scholes et al. 2018).

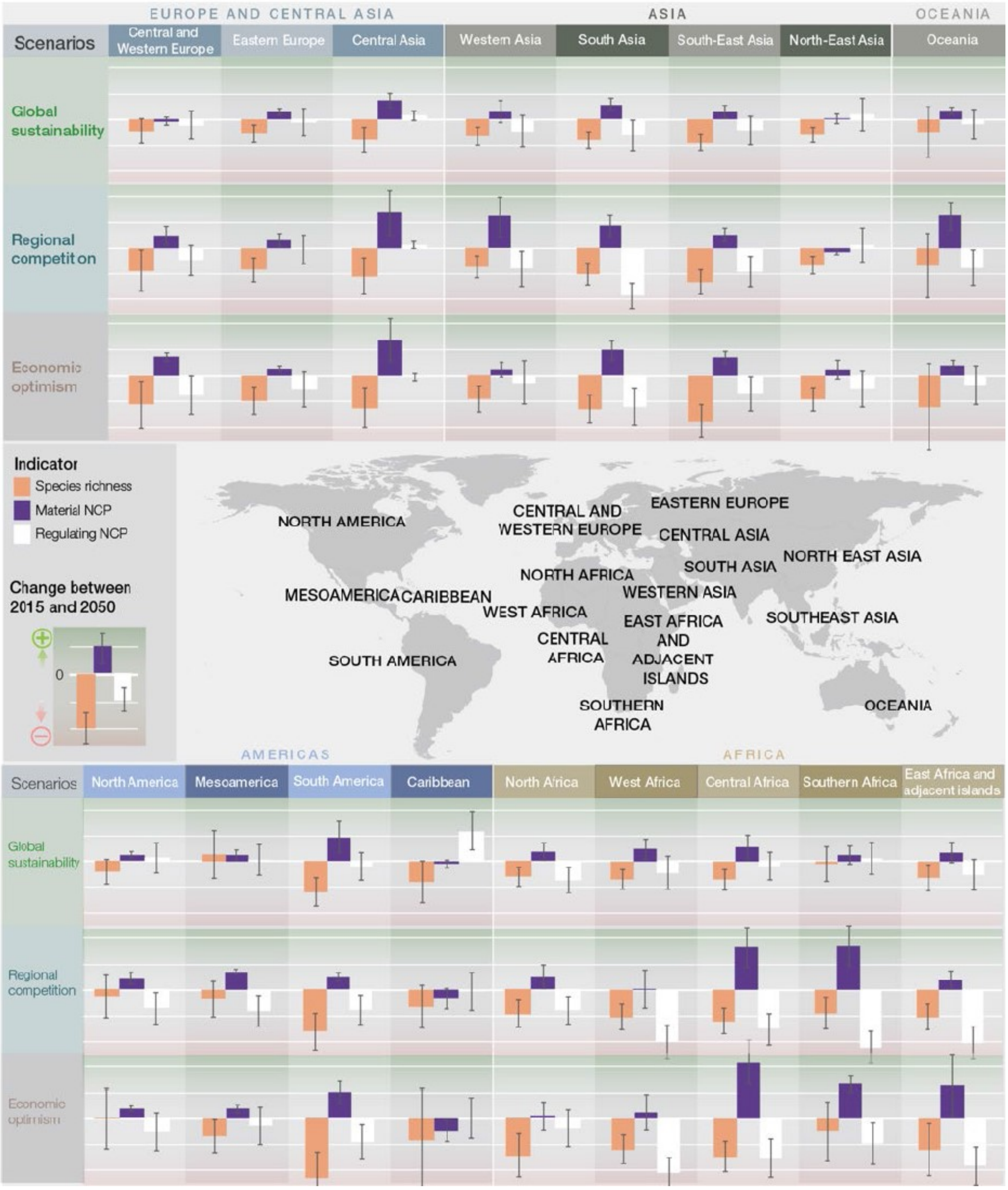

Figure 7.19 Projections of impacts of land use and climate change on biodiversity and nature's material and regulating contributions to people between 2015 and 2050. Note: (1) The 'Global Sustainability' scenario combines proactive environmental policy and sustainable production and consumption with low greenhouse gas emissions ((SSP1, RCP2.6: top rows in each panel. (2) The 'Regional Competition' scenario combines strong trade and other barriers and a growing gap between rich and poor with high emissions (SSP3, RCP6.0: middle rows). (3) The 'Economic Optimism' scenario combines rapid economic growth with low environmental regulation with very high greenhouse gas emissions (SSP%, RCP8.5; bottom rows). (4) Multiple models were used with each of the scenarios to generate the first rigorous global-scale model comparison estimating the impact on biodiversity (changes in species richness across a wide array of terrestrial plant and animal species at regional scales; orange bars), material NCP (food, feed, timber and bioenergy; purple bars), and regulating NCP (nitrogen retention, soil protection, crop pollination, crop pest control and ecosystem carbon; while bars). The bars are the normalised means of multiple models and whiskers indicate the standard errors. Source*:* SPM Figure 8 (Díaz et al. 2019).

7.6.6 The feasibility of mitigation within AFOLU

The assessment presented in Table 7.10 explores the feasibility of AFOLU mitigation options, following a format used by all sectoral chapters within this report (Chapters 4-11). Assessment considers six feasibility criteria; geophysical, environmental-ecological, technological, economic, socio cultural and institutional, with several sub-categories within each criterion. Full description of the methodology is provided in Chapter 6. In this case, assessment combines the discussion presented in Section 7.4 regarding co-benefits, resource needs, potential risks and technological readiness of specific mitigation measures. Furthermore, the assessment table provides an overview of considerations given in previous parts of Section 7.6, regarding policy options, linkage with ecosystem services, human well-being and adaptation.

The 20 mitigation measures identified in Section 7.4 have been re-categorised into eight mitigation options; (1) reduce food loss and waste (2) shift to sustainable healthy diets (3) reduce non-CO_2 emissions from agriculture (4) restore forests and other ecosystems (5) enhance carbon in agricultural systems (6) protect and avoid conversion of forests and other ecosystems (7) sustainably manage forests and other ecosystems (8) bioenergy from material side streams and BECCS.

As emphasised throughout this chapter, the AFOLU sector is highly diverse, with considerable variation in land management regionally due to the complex interaction between multiple factors and drivers, while involving a significant number and range of stakeholders. Therefore, the feasibility of mitigation options is highly context specific. Interpretation of the following high-level assessment must be with caution.

Considering geophysical indicators, most measures score a mixed to positive rating, suggesting that either geophysical barriers do not generally limit measures and potential mitigation delivery (i.e. notably concerning protection measures such as reduced deforestation), or that measures may positively impact geophysical resource, for example by reducing pressure on land (i.e. through reduce food waste, changed diets). However, some measures (e.g. afforestation, large scale protection or BECCS), if deployed at very large scales may increase pressure on land, thus indicating clear geophysical limits. In the case of use of residues for bioenergy, there is less pressure on land, but there are limits to the volumes available. Geophysical dimensions can also impact measures relating to reduction of non-CO_2 emissions in agriculture or increasing carbon on agricultural land. For example, increased use of grain in livestock diets may drive land use change in certain contexts, while capacity for soil carbon sequestration varies greatly according to soil type and climatic factors, regardless of soil management. In all cases, the impact of geophysical dimensions is highly context specific.

For environmental indicators, most measures score quite positively especially on water and on biodiversity, with exceptions on large-scale afforestation and BECCS. On toxics and air pollution the evidence is more mixed or not applicable. Regarding the air pollution effects of bioenergy, the feasibility fully depends on the quality of the air purification installation.

On the technological indicators, most measures score quite positively. Characteristically for AFOLU, most measures (from diets to ecosystem restoration and protection and soil carbon) are very well known. Still, (long term) success is by far not always guaranteed, but this comes back in institutional and socio-cultural criteria. Furthermore, appropriate implementation in the field does require investments in training and well-educated staff.

Most measures score highly on the economic indicators, depending on circumstances, and score significantly different from low cost to extremely high. For example, on non-CO_2, some measures require considerable capital investment or are costly to operate, such as large-scale anaerobic digestion plants or other manure management systems. In contrast, other measures are cost negative or neutral to implement and may lead to cost savings, such as improved crop nutrient management or water management in rice paddy systems).

Many AFOLU measures will face challenges like acceptance, implementation with millions of landowners, managers, or users, among others, on the socio-cultural indicators. Extensive afforestation and BECCS create substantial changes across wide areas and will face challenges to acceptance on multiple grounds (from land use to food price). Attempts to change diets will face significant cultural barriers. Also, large-scale land use changes may, in some cases (when well designed), help locals, but in other cases may deprive them of their land.

Some measures also show the challenges in the AFOLU sector on the institutional indicators: capacity is essential to achieving long-term effects. Many indicators show mixed effects depending very much on the country. For example, on non-CO_2 improved knowledge transfer and support from agricultural advisory services and educational institutions are crucial for implementing all measures. Variables as effectiveness, persistence, and indirect impacts (e.g., breeding of low emitting animals, tannins & vaccines) need further research. Availability of capital and limited access to finance/credit from associated institutions may limit adoption in some instances.

Table 7.10 An assessment of the feasibility of eight AFOLU mitigation options considering geophysical, environmental-ecological, technological, economic, socio cultural and institutional factors

Mitigation Options	Scenario Results from AR6 database for Paris consistent policies (1.5 and 2°C): full scenario ensemble if not otherwise specified. Scenario number changes by reporting variable		1. Geophysical											
			Physical potential				Geophysical recourses				Land Use			
	variable definition	scenarios mean and inter-quartile range	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste			±			Climate conditions—humidity, temperature, insolation—may favour food loss for putrescible food products Reducing food waste and food loss minimize the need for agricultural expansion for producing excess food. Heat stress result in yield losses, lower product quality, and increase food loss.	±			Reducing food loss and waste related to inputs use to zero might not be feasible, but any action will reduce the use of fossil fuel used for food processing	+			Reduced food loss will reduce demand for new agricultural land
Healthy balanced diets, rich in plant-based food (less animal-based)	Share of crops over food demand in sustainable development IP in 2020 and 2050 (%)	57 -> 72	+			healthy diets will reduce demand for agricultural land	+			healthy diets will reduce demand for agricultural land	+			healthy diets will reduce demand for agricultural land
Reduce non-CO_2 emissions from agriculture	CH_4 emissions from agriculture: 2020 and 2050 (Mt)	162 -> 121 [99-145]	±	3	4	Highly context specific (e.g. increased use of concentrates or grain as livestock feed is dependent on land availability to produce feed crops. Improved grazing/forage management may be dependent on localized weather and soil conditions. For other measures (e.g. vaccines, synthetic inhibitors), physical constraints are not applicable)	±	3	4	Highly context specific (e.g. increased use of concentrates or grain may be limited by land resources available for feed production. Other agricultural measures are not dependent on land availability)	±	3	4	Highly context specific (e.g. increased use of concentrates or grain as livestock feed may drive Land Use Change (LUC). However, other agricultural measures are not restricted by land availability)
Restore forests and other ecosystems	Forest cover: 2020 and 2050 (Mha)	3924 -> 4228 [4015-4483] ha 390-5800 Mt CO2/y (median 1600 Mt CO2/y)	±	3	3	Physical potential is very large , in the past large areas have been degraded /deforested. In principle large areas are available , but in practice it starts to compete with food provision etc	+	5	5	Physical potential is very large , in the past large areas have been degraded /deforested. In principle large areas are available , but in practice it starts to compete with food provision etc	±	3	3	Physical potential is very large , in the past large areas have been degraded /deforested. In principal large areas are available , but in practice it starts to compete with food provision etc
Enhance carbon in agricultural systems	AFOLU CO2 emissions: 2020 and 2050 (Gt)	3.3 -> -1.5 [-3-0]	+	4	4	Type of agriculture (with trees, integration of animals, types of crops), climate	-	3	3	Use of biofuel emit carbon. Biochar and are technically intensive and covers limited scales. May not work in low income countries	±	3	3	Depends to the land use type, time since land use change and previous land use, new demand for agricultural land, loss of forest cover, promotion of agroforestry, land tenure systems in place
Protect and avoid conversion of forests and other ecosystems	AFOLU various ecosystem reductions of conversions (Mt CO2/y)	1830-8800	+	5	5	Physical potential is very large , in the past large areas have been degraded /deforested.	+	5	5	Physical potential is very large , in the past large areas have been degraded /deforested.	±	3	3	Other pressures on land remain, for food, etc.
Sustainably manage forests and other ecosystems	Maintenance of CO2 sink function as well as provision of renewable resources, conservation of biodiversity (e.g. wood for buildings, bioenergy) (Mt CO2/y)	894 (under 100$/t CO2) (320-2890)	±	3	3	Improving forest management requires proper management skills, investments , access to forests, etc.	±	3	3	Can only be applied on accessible managed forests, preferably not in primary forests. Maximum some 2 billion ha Available, but in proactive far less: < 1 billion ha	+	5	5	Can be applied on accessible managed forests. Does not put a claim on land
Bioenergy from side streams and BECCS	emission reductions from bioenergy derived from side streams or dedicated crops Mt CO2/y	5000-7000	±	3	3	Physical potential of side streams is large (few billion tonnes material) . also physical potential of dedicated crops is large, But depends heavily on other land uses, agricultural management and intensification. In the past large areas have been degraded /deforested. In principle large areas are available (up to few hundred Mha) , but in practice it starts to compete with food production etc	±	3	3	Physical potential of side streams is large (few billion tonnes material) . also physical potential of dedicated crops is large, in the past large areas have been degraded /deforested.(up to few hundred Mha)	±	3	3	Depends heavily on other land uses, agricultural management and intensification, and forest management. Can be mitigated by using residues.. Physical potential of side streams is large (few billion tonnes material) and does not compete for land. Physical potential of dedicated crops will start to compete with food at scales more than 200-300 Mha

Mitigation Options	2. Environmental-ecological															
	Air pollution				Toxic waste, ecotoxicity eutrophication				Water quantity and quality				Biodiversity			
	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste	±			Unavoidable food waste can be recycled to produce energy based on biological, thermal and thermochemical technologies and reduce some forms of use of fossil fuel (e.g. biogas)	+			less losses will reduce demand for resources, and lead to less use of fertilizer or pesticides etc.	+			less losses will reduce demand for resources, and lead to less use of water etc.	+			less losses will reduce demand for resources, and lead to less pressure on biodiversity etc.
Healthy balanced diets, rich in plant-based food (less animal-based)	±			healthy diets will reduce demand for resources, and lead to less use of fertilizer or pesticides etc.	+			healthy diets will reduce demand for resources, and lead to less use of fertilizer or pesticides etc.	±			healthy diets will reduce demand for agricultural land, and will lead to less water use but many people in world still need more access to food	+			healthy diets will reduce demand for agricultural land, and will lead to less pressure on biodiversity, but many people in the world still need more access to food
Reduce non-CO_2 emissions from agriculture	±	4	4	Highly context specific (e.g. some manure management measures may be antagonistic with ammonia (NH_3) emissions or other GHGs. Fugitive CH_4 emissions from AD plants can be a considerable problem. Amended livestock diets may reduce CH_4 emissions but increase N_2O from increased N excretion. CO_2 emissions from the production and transport of feedstocks for large-scale AD may offset benefits, while water management in rice paddy systems may reduce CH_4 but increase N_2O emissions)	±	3	4	Highly context specific (e.g. some CH_4 inhibitors or dietary additives may cause toxicity in animals or impact meet and milk quality. Bromoform compounds in seaweed may have ozone impacts as well as human health issues. Increased feeding of concentrates may cause acidosis in ruminants. However. improved manure management, nitrogen fertilizer management or application of nitrogen inhibitors to pasture may prevent environmental degradation)	±	2	4	Context specific but generally positive where applicable (e.g. improved nitrogen fertilizer management or application of nitrogen inhibitors may prevent leaching and conserve water quality, water management in rice paddy systems may reduce water usage)	±	2	4	Highly context specific (e.g. a shift from forage to concentrate animal feed may drive LUC, impacting biodiversity. Commercial/industrial supply of novel dietary additives (e.g. seaweed) may have environmental impacts while other measures such CH_4 inhibitors will have limited impact on biodiversity)
Restore forests and other ecosystems	±	2	2	It can help in catching in dust	NA				±	3	3	reforestation can have effects on groundwater and streams. When reforestation and restoration means planting large scale plantations, then effects are more diverse and can be negative . Depends very much on local situation. Reforestation can also help to maintain soils and thus groundwater reserves, it can also lead to more cloud formation	±	3	3	depending how it is done, reforestation, restoration of peatland and restoration of wetlands can have multiple effects and diverse effects on biodiversity. depending on the forest types and management, management also creates landscape diversity. When reforestation means planting large scale plantations, then effects can be negative on biodiversity. Depends also on local situation and cultural historical aspects
Enhance carbon in agricultural systems	±	3	3	Limited growth due to air pollution in case of biochar. Crops contributes to the reduction of air pollution. Intensive agriculture system contributes to air pollution. The use of pesticide has some remanence affecting air quality. Air pollution affect yield quality (food waste) leading to more demand for land and more GHG emission	-	3	3	Food waste due to toxic waste in case many different sludges are applied. . Eutrophication affect water quality that can be used for irrigation. Waste water from farms are nutrition rich exudates that can results in downstream eutrophication Use of pesticides and chemical fertilizers	±	3	3	Water scarcity to the use of water in agriculture from irrigation to transformation. But in case of extra addition of organic material to soils, it is beneficial to water delivering capacity	+	4	4	Increased biodiversity in agricultural land improved GG uptake and soil quality
Protect and avoid conversion of forests and other ecosystems	+	4	4	reduction of degradation would certainly reduce air pollution from fires	NA				+	4	4	reducing deforestation mostly has positive effects on groundwater and streams. Depends very much on local situation. helps to maintain soils and thus groundwater reserves, it can also lead to cloud formation	+	5	5	reducing deforestation and degradation has positive effects biodiversity
Sustainably manage forests and other ecosystems	NA				+	5	5	Change of management can have some effects on nutrient flow to groundwater, and streams, but this improved management should actually improve the situation	±	3	3	Change of management can have some effects on groundwater and streams. The improved management should improve the situation. When improved management means planting large scale plantations, then effects are more diverse and can be negative . Depends very much on local situation	±	3	3	Change of management can have multiple effects and diverse effects on biodiversity. Management also creates landscape diversity. When management means planting large scale plantations, then effects can be negative on biodiversity. Depends also on local situation and cultural historical aspects. some forests have been managed already hundreds of years creating very specific biodiversity
Bioenergy from side streams and BECCS	±	3	3	depends fully on quality of the air purification installation	±	3	3	Extent depends on crop and management system, and whether it concerns dedicated crops or residue streams.	±	3	3	dedicated crops may extract lot of groundwater, but it depends on how the dedicated crops are designed in the landscape. Likely to need increased irrigation leading to water availability issues	±	3	3	depends very much on the scale, when it concerns side stream from forestry or agriculture, there may not be much harm to biodiversity. When it concerns massive dedicated crops (> 300 Mha) , biodiversity will be harmed . 1st generation crops mostly negative. Advanced bioenergy crops (SRC, miscanthus, switchgrass) can have positive effects

	3. Technological											
Mitigation Options	Simplicity				Technological scalability				Maturity and technology readiness			
	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste	+			Reduction, Recovery and Recycle food waste. Reducing food loss/waste can be achieved through improved harvesting techniques, on-farm storage, infrastructure, and packaging.	+			Improved harvesting techniques, on-farm storage, infrastructure, packaging to keep food fresher for longer, use renewable energy for food product transformation Efficiency of food processing and transportation.	±			Context matters in technology maturity. A technology suitable for a context is not necessarily appropriate for another GHG emissions associated with energy consumption and the source of energy used
Healthy balanced diets, rich in plant-based food (less animal-based)	±			healthier diets will be beneficial to many in western world with an overconsumption. Technically it is relatively simple, but in practice very difficult	±			healthier diets will be beneficial to many in western world with an overconsumption. Technically it is relatively simple, but in practice very difficult. Also billions of people are still undernourished, they need more access to food. And better food. Furthermore, eating meat is deeply embedded in many cultures.	±			Technologically it is ready. healthier diets will be beneficial to many in western world with an overconsumption. Technically it is relatively simple, but in practice very difficult. Also billions of people are still undernourished, they need more access to food. And better food. Furthermore, eating meat is deeply embedded in many cultures.
Reduce non-CO_2 emissions from agriculture	±	3	4	Highly context specific (e.g. physical administration of some measures (e.g. inhibitors, dietary lipids) is challenging in pasture-based systems, while other measure are specially designed for intensive systems (e.g. slurry management -solid/liquid separation). Some measures (e.g. large-scale AD) require considerable expertise, though others are relatively simple such as covering manure storage facilities or water management in rice paddy systems)		3	4	Highly context specific (e.g. improved livestock husbandry has more impact in underperforming systems thus limiting universal adoption and measure effectiveness. Some measures are only applicable to large-scale or intensive systems. Large-scale AD may not suit existing farming systems, due to insufficient feedstock supplies, while plants require grid connectivity. Also, persistence of some measures, such as CH_4 inhibitors is unclear)	±	3	4	Highly context specific (e.g. some measures such as vaccines, early life programming in ruminants, are in early stages of development. Other measure can be implemented immediately such as water management in rice paddy systems, improved crop nutrient management or improved livestock husbandry)
Restore forests and other ecosystems	±	4	4	In principle rather simple, but skilled people are needed, and good knowledge of local climate, soils etc.	±	4	4	Can be easily scaled , provided the right soc-economic setting is available, land is available etc	+	5	5	very much ready, although it needs to be adapted locally always
Enhance carbon in agricultural systems	±	4	4	Type of machineries (use of energy or animal traction), farming technology used (tillage, no tillage, mulching, biodiversity conservation)	±	4	4	Technological options scaled will influence emission. Scaling technology depends on the type of agriculture, the financial and institutional barriers.	+	4	4	This depends to the purpose. Productivity approaches differ from those promoting resilience and the choice will influence the technology options and their readiness
Protect and avoid conversion of forests and other ecosystems	±	4	4	In principle rather simple, but still under the many other pressures on land it is very difficult to execute without leakage	±	4	4	In principle rather simple to scale to many regions, but still under the many other pressures on land it is very difficult to execute without leakage	+	5	5	In principle very mature
Sustainably manage forests and other ecosystems	±	4	4	In principle rather simple, but still highly skilled people are needed	+	4	4	Can be easily scaled , provided the right economic setting is available, including access to forests etc	+	5	5	very much ready, although it needs to be adapted locally always
Bioenergy from side streams and BECCS	±	4	4	On residues streams, in principle rather simple, but still highly skilled people are needed for agriculture & forest management and logistics. BECCS (i.e. storing in underground reservoirs) requires CO_2 capture, pumping, transport, centralisation and injection systems. Advanced biofuels depend on complex thermochemical reactions.	±	4	5	In principle rather simple to scale to many regions, but still under the many other pressures on land and when done massively, it is very difficult to execute without leakage or LUC. Large scale BECCS (i.e. storing in underground reservoirs) drives down costs, especially for BECCS	+	5	5	In principal very mature. 1st generation bioenergy is widely available. Advanced bioenergy options (lignocellulosic fuels, BECCS) exist but are not commercial right now

	4. Economic							
Mitigation Options	Costs in 2030 and long term				Employment effects and economic growth			
	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste	+				±			
Healthy balanced diets, rich in plant-based food (less animal-based)	+				±			
Reduce non-CO_2 emissions from agriculture	±	3	4	Highly context specific (e.g. some measures require considerable capital investment or are costly to operate, such large scale AD plants or other manure management systems, while other measures are cost negative or neutral to implement and may lead to cost savings such as improved crop nutrient management or water management in rice paddy systems)	±	2	3	Highly context specific (Generally limited impact on employment but evidence suggests some measures (e.g. improved crop nutrient management, manure management or water management in rice paddy systems) may generate cost savings and therefore indirectly positively effect economic growth)
Restore forests and other ecosystems	+	4	4	relatively cheap, but depends very much on long term success and maintenance.	±	3	3	depends what previous land use was.
Enhance carbon in agricultural systems	±	3	3	Cost of food affects area cultivated for a given crop (market drivers). High input costs may lead to higher yield but result to higher GHG emission	±	2	2	Labour allocation varies depending to the technology in place and labour availability.
Protect and avoid conversion of forests and other ecosystems	+	4	4	relatively cheap, but depends very much on long term success and maintenance.	±	3	3	depends what alternative land uses.
Sustainably manage forests and other ecosystems	±	3	3	the net additional effect in terms of carbon sink is not very large per ha, but additional benefits exist in terms of provision of wood, or biodiversity	+	4	4	will give additional employment, also downstream the wood chain
Bioenergy from side streams and BECCS	±	3	3	costs are relatively high. Subsidies are needed. Costs of BECCS are expected to fall due to technological learning and increased scale. Application of carbon prices may also help increasing competitiveness.	+	4	4	will give additional employment, also downstream the wood chain . Bioenergy can become an important export commodity for many countries. Long supply chain can also stimulate employment.

	5. Socio-cultural											
Mitigation Options	Public acceptance				Effects on health & wellbeing				Distributional effects			
	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste	+			Changes in behaviours and attitudes of a wide range of stakeholders across the food system will play an important role in reducing food loss and waste.	+			Better diets	±			Regional differences exist in food loss and waste and all parts of food supply chains need to become efficient to achieve the full reduction potential of food loss and waste. Reducing losses in principle could lead to better distribution of available food.
Healthy balanced diets, rich in plant-based food (less animal-based)	±			healthier diets will be beneficial to many in western world with an overconsumption. Billions of people undernourished, they need more access to food. And better food. Furthermore, eating meat is deeply embedded in many cultures.	+			healthier diets will be beneficial to many in western world with an overconsumption. For these it will be beneficial.	+			Reducing losses in principle could lead to better distribution of available food.
Reduce non-CO_2 emissions from agriculture	±	3	5	Highly context specific (e.g. some measures (nitrogen or CH_4 inhibitors, additives) may have low public acceptance regarding animal welfare or human health concerns. Large-scale manure management measures may be opposed by local communities, while farmers' perceptions, potential reluctance to change or risk-adversity may limit adoption. Other measures such as water management in rice paddy systems or improved crop nutrient management should be publicly acceptable)	±	3	4	Highly context specific (e.g. measures may benefit overall productivity, thus food security while also enhancing resource use efficiency (improved crop nutrient management, water management in rice paddy systems, improved livestock husbandry). However, other measures may negatively impact yields and therefore, food security such as increased use of gain as livestock feed may not be appropriate in developing countries where food security may be of concern)	±	1	2	Highly context specific (e.g. measure implementation cost burdens may not be distributed evenly across agricultural sectors)
Restore forests and other ecosystems	±	3	3	acceptance not always that high , as it may lead to competition for land	NE				±	3	3	depends very much on local involvement . Sometimes communities benefit.
Enhance carbon in agricultural systems	+	4	4	Cultural context matters for agricultural systems. Public rejection leads to failure of farming option	+	2	2	Improved diet using quality food products. Diversified diet	0	2	2	
Protect and avoid conversion of forests and other ecosystems	+	4	4	tends to be highly positively accepted in areas far away from the deforestation. Local people may need the land for food	NE				±	3	3	Local people may need not always benefit
Sustainably manage forests and other ecosystems	+	4	4	improved management will lead to better forests that generally are wider accepted	NE				NE			
Bioenergy from side streams and BECCS	-	4	4	acceptance in some countries very low, perceived as leading to deforestation and LUC	-	4	4	acceptance in some countries very low, perceived as leading to more pollution. But proven effects on health unclear.	±	3	3	Local people may need not always benefit

	6. Institutional											
Mitigation Options	Political acceptance				Institutional capacity & governance, cross-sectoral coordination				Legal and administrative feasibility			
	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context	Rating Feasibility	Level of agreement	Level of confidence	Context
Reduce food loss and waste	+			most governments will accept this as a good measure	±			most governments will accept this as a good measure but implementation will vary a lot	±			most governments will accept this as a good measure but implementation will vary a lot
Healthy balanced diets, rich in plant-based food (less animal-based)	±			eating meat is deeply embedded in many cultures.	±			most governments will accept this as a good measure but implementation will vary a lot	-			eating meat is deeply embedded in many cultures. Very difficult to tell people what to eat.
Reduce non-CO_2 emissions from agriculture	-	3	5	Limited policy support has historically limited adoption of agricultural measures. Policy support and investment in education and research is considered crucial for implementation, while international agreement may be necessary to prevent potential leakage effects.	-	3	5	Improved knowledge transfer and support from agricultural advisory services and educational institutions is crucial for implementation of all measures. Further research and developed is needed for specific measures regarding effectiveness, persistence and indirect impacts (e.g. breeding of low emitting animals, tannins & vaccines). Availability of capital and limited access to finance/credit from associated institutions may limit adoption in certain cases.	±	3	5	Highly context specific (e.g. some measures (e.g. CH_4 inhibitors for ruminants) are at advanced stages of development but still require regulatory approval for commercial use. Large-scale AD plants may face planning restrictions. Other measures are technically well established and do not face legal barriers)
Restore forests and other ecosystems	±	3	3	depends very much on local circumstances, other pressures on land, perceived need to restore etc	±	3	3	depends very much on the country.	±	3	3	depends very much on local circumstances, other pressures on land, perceived need to restore etc
Enhance carbon in agricultural systems	+	3	3	Acceptance of Climate change policies is a conduit to improved sectoral efforts on mitigation. Political acceptance leads to more clarity about mitigation responses along the development pathway depending to the country priority areas.	+	2	2	The standardized institutional operation and factors modulating governance, come with differentiated set of options that all require knowledge to address mitigation issues. The private sector also operates with nested processes and skills that can contribute to various mitigation responses.	+	2	2	Laws and regulations are the frameworks for due diligence and compliance. Climate negotiations comes with actionable solutions that often trigger new regulation and administrative process (safeguards, countermeasures)
Protect and avoid conversion of forests and other ecosystems	±	3	3	depends very much on the country.	±	3	3	depends very much on the country.	±	3	3	depends very much on the country.
Sustainably manage forests and other ecosystems	+	4	4	Very much depends on the country but in principle governments will strive for better forest management often	±	3	3	Very much depends on the country	±	3	3	Very much depends on the country
Bioenergy from side streams and BECCS	±	3	5	Very much depends on the country . BECCS may be an enabler for CDR and net-zero pathways	±	3	3	Very much depends on the country, Global sustainability criteria needed to avoid leakage of emissions and other environmental damages	±	3	3	Very much depends on the country

7.7 Knowledge gaps

Research, outreach and implementation tests are crucial in advancing mitigation within AFOLU, regarding a range of areas from emissions accounting methodology to mitigation measure development and sustainable implementation. The following knowledge gaps are identified as priorities for research;

- There is on-going need to develop and refine emission factors and improve activity data for inventory accounting. For example, lack of knowledge on CO_2 emissions relating to forest management and burning or draining of organic soils (wetlands and peatlands), limits certainty on CO_2 fluxes. Specifically concerning N_2O, there is need for improved modelling of land and ocean emission processes, as well as more comprehensive monitoring of atmospheric N_2O in regions currently under-represented (Tian et al. 2020).
- There is need to understand the role of forest management, carbon fertilisation and associated interactions in the current forest carbon sink that has emerged in the last 50 to 70 years. These aspects are likely to explain much of the difference between bookkeeping models, which do not account for management, and empirical observations.
- Continued research into novel and emerging mitigation measures and its cost efficiency (e.g. CH_4 inhibitors or vaccines for ruminants) is required. In addition to developing specific measures, research is also needed into best practice around measure implementation and optimal management at regional and country level. For example, the management and restoration of tropical ecosystems need more field-based measurements.
- Sustainable intensification within agriculture has been suggested to be a mechanism for mitigation, whereby changes in production on existing agricultural land either prevents agricultural area expansion or facilitates existing agricultural land to be spared for non-agricultural uses such as afforestation (Godfray et al. 2014; Olsson et al. 2019; Mbow et al. 2019). Though theoretically plausible, realising mitigation potential via these mechanisms is likely to be challenging, considering socio-economic and cultural barriers. Further research into the feasible mitigation potential of sustainable intensification in terms of absolute emissions, is required.
- There is need to understand the role of property rights in the preservation of forest carbon stores in tropical forests in Latin America, Africa, and South-east Asia.
- Mitigation potential estimates, whether derived from sectoral studies or IAMs generally do not account for biophysical climate effects, mitigation permeance nor impacts of future climate change and corresponding feedbacks. The SRCCL noted that in-action on climate change threatens land-based mitigation potentials and may turn residual land sinks into sources (Jai et al. 2019). Research is therefore urgently needed on impacts of global warming on land-based mitigation activities at a country-level, particularly those that sequester carbon.
- There is a need to develop a more comprehensive and robust portfolio of land-based mitigation measures relevant at country-levels, taking into account trade-offs, costs and relevance to achieving SDGs. Studies are needed that provide spatially explicit marginal abatement cost curves (MACCs) and mitigation potential estimates for additional land-based activities, such as reduced conversion and restoration of coastal marshes and seagrass, and of grasslands and savannas. Additionally, land use change behaviour parameters lack empirical foundations in general, notably with respect to energy plantations.
- There is a lack of understanding of socio-economic, institutional and other barriers to implementing mitigation measures. Estimated economic potential can indicate some level of

feasibility, however, the inclusion of other social, political, and environmental considerations in estimating potentials would greatly advance mitigation estimates.

- Mitigation measures have important synergies, trade-offs and co-benefits impacting biodiversity and resource-use, human-well-being and ecosystem services. However, there is a need for more studies to understand how these interactions and relationships vary across localities and contexts. Data on country-level trade-offs and co-benefits would aid country-level planning considerably. While important progress has been made in considering the impact of measures on, for example food security, most modelled scenarios do not examine impacts on poverty, employment and development, important factors that are highly context specific and vary enormously by region.
- Targets for nature need to be refined to fit in with the metrics tracked by the SDGs.
- Specifically concerning IAMs, expanding the portfolio of land-based mitigation measures would be very helpful in assessing the wider range of AFOLU potentials, while taking cross-sectoral dynamics and trade-offs into account.
- There is need to develop policy options to allow agricultural soil and forest carbon to be utilised by voluntary or regulatory markets as offsets in order to increase the availability of capital in natural climate solutions. Novel constructions between private finance and public governance need to be urgently constructed and tested. Regulations that hamper more climate friendly land use and lock in of subsidy schemes also hampering mitigation need to be urgently changed.

7.8 Frequently asked questions

FAQ 7.1 Why is the Agriculture, Forestry and Other Land Use (AFOLU) sector unique when considering Greenhouse Gas (GHG) mitigation?

There are three principle reasons that make AFOLU unique in terms of mitigation;

1. In contrast to other sectors, AFOLU can facilitate mitigation through several different pathways. Specifically, AFOLU can (a) reduce emissions as a sector in its own right, (b) remove meaningful quantities of carbon from the atmosphere and relatively cheaply, and (c) provide raw materials to enable mitigation within other sectors, such as energy, industry or the built environment.
2. The emissions profile of AFOLU differs from other sectors, with a greater proportion of non-CO_2 gasses (N_2O and CH_4) arising from AFOLU. The impacts of mitigation efforts within AFOLU can vary according to which gasses are targeted, as a result of the differing atmospheric lifetime of the gasses and differing global temperature responses to the accumulation of the specific gasses in the atmosphere. This makes reporting aggregated AFOLU emissions, estimating relative mitigation potential and forming mitigation pathways for meeting climate objectives challenging (see Box 2.2 and Appendix A.B.10 on GHG emission metrics).
3. AFOLU is inextricably linked with some of the most serious challenges that are suggested to have ever faced humanity, such as large-scale biodiversity loss, environmental degradation and the associated consequences. As AFOLU concerns land management and utilises a considerable portion of the Earth's terrestrial area, the sector greatly influences soil, water and air quality, biological and social diversity, the provision of natural habitats, and ecosystem functioning, consequently impacting many SDGs. In addition to tackling climate change, AFOLU mitigation measures have capacity, where appropriately implemented, to help address some of these wider challenges, as well as contributing to climate change adaptation.

FAQ 7.2 What AFOLU measures have the greatest economic mitigation potential?

Mitigation measures in forests and other ecosystems provide the largest share of economic (up to USD100/tCO_2 yr^{-1}) mitigation potential, followed by agriculture and demand-side measures. Reduced conversion (protection), enhanced management, and restoration of forests, wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester carbon by 6.1 (±2.9) GtCO_2eq yr^{-1}, with measures that 'protect' having the highest mitigation densities (mitigation per area). Agriculture provides the second largest share of mitigation, with 3.9 ± 0.2 GtCO_2-eq yr^{-1} potential, from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to healthy diets and reducing food waste, can provide 1.9 GtCO_2-eq yr^{-1} potential (accounting only for diverted agricultural production and excluding land-use change). Demand-side measures reduce agricultural land needs and land competition and can complement or enable supply-side measures such as reduced deforestation and reforestation.

FAQ 7.3 What are potential impacts of large-scale establishment of dedicated bioenergy plantations and crops and why is it so controversial?

The potential of bioenergy with carbon capture and storage (BECCS) remains a focus of debate. BECCS involves sequestering carbon through plant growth and capturing the carbon generated when the crops are burned for power or fuel. While these processes in isolation appear to create a carbon-negative outcome, BECCS requires cropland, water and energy which can create adverse side-effects at scale. Controversy has arisen because some of the models calculating the energy mix required to keep the temperature to 1.5°C have included BECCS at very large scales as a means of both providing energy and removing carbon to offset emissions from industry, power, transport or heat. For example, studies have calculated that for BECCS to achieve 11.5 $GtCO_2$-eq per year of carbon removal in 2100, as envisaged in one scenario, 380-700 Mha or 25-46% of all the world's arable and cropland would be needed. In such a situation, competition for agricultural land could threaten food production and food security. More recently however, the scenarios for BECCS have become much more realistic. However, where bioenergy is part of the full agriculture or wood chain, from sustainably managed forest or specialised plantations, it will deliver positive GHG balances. Progress is important because if BECCS is not a feasible option at a large scale then deeper transformation will be required in other areas, or ambitious climate targets will have to be given up altogether.

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