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Mitigation in the AFOLU sector

Emissions, removals, inventories and reflections on solutions for national policymakers

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Disclaimers

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Ky0n Cheng, "Terraced rice field". Flickr.

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Glossary

Term	Definition
Activity data	Data on the magnitude of a human activity resulting in emissions or removals taking place during a given period of time. In the Agriculture, Forestry and Other Land Use (AFOLU) sector, data on area of different land uses, management systems, animal numbers, lime and fertiliser use are examples of activity data.
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
Afforestation	Conversion to forest of land that historically has not contained forests. [Note: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, in the context of reporting and accounting Article 3.3 and 3.4 activities under the Kyoto Protocol, see 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.] See also *Reforestation*, *Deforestation*, *Forest* and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*
Agriculture, Forestry and Other Land Use (AFOLU)	In the context of national greenhouse gas (GHG) inventories under the United Nations Convention on Climate Change (UNFCCC), AFOLU is the sum of the GHG inventory sectors Agriculture and Land Use, Land-Use Change and Forestry (LULUCF); see the 2006 IPCC Guidelines for National GHG Inventories for details. Given the difference in estimating the 'anthropogenic' carbon dioxide (CO_2) removals between countries and the global modelling community, the land-related net GHG emissions from global models included in this report are not necessarily directly comparable with LULUCF estimates in national GHG Inventories. FOLU (Forestry and Other Land Use) – also referred to as LULUCF: The subset of AFOLU emissions and removals of greenhouse gases (GHGs) resulting from direct human-induced land use, land-use change, and forestry activities excluding agricultural emissions.
Agroecology	'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'.
Agroforestry	Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components. Agroforestry can also be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels (FAO, 2015a).
Baseline scenario	In much of the literature the term is also synonymous with the term business-as-usual (BAU) scenario, although the term BAU has fallen out of favour because the idea of business as usual in century-long socio-economic projections is hard to fathom. In the context of transformation pathways, the term baseline scenarios refer to scenarios that are based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy effort. Typically, baseline scenarios are then compared to mitigation scenarios that are constructed to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations or temperature change. The term baseline scenario is often used interchangeably with reference scenario and no policy scenario. See also *Emission scenario*, and *Mitigation scenario*.
Biochar	Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce greenhouse gas (GHG) emissions from biomass that would otherwise decompose rapidly(IBI, 2018).
Biodiversity	Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN, 1992). See also *Ecosystem*, and *Ecosystem service*.
Bioenergy	Energy derived from any form of biomass or its metabolic by-products. See also *Biomass* and *Biofuel*.
Bioenergy with carbon dioxide capture and storage (BECCS)	Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere. See also *Bioenergy*, and *Carbon dioxide capture and storage (CCS).*
Biofuel	A fuel, generally in liquid form, produced from biomass. Biofuels include bioethanol from sugarcane, sugar beet or maize, and biodiesel from canola or soybeans. See also *Biomass*, and *Bioenergy*
Biomass	Organic material excluding the material that is fossilised or embedded in geological formations. Biomass may refer to the mass of organic matter in a specific area (ISO, 2014). See also *Bioenergy*, and *Biofuel*. Traditional biomass: The combustion of wood, charcoal, agricultural residues and/or animal dung for cooking or heating in open fires or in inefficient stoves as is common in low-income countries.
Business as usual	See *baseline scenario*

Carbon dioxide (CO_2)	A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a Global Warming Potential (GWP) of 1. See also *Greenhouse gas (GHG)*, *Land use*, and *Land-use change*.
Carbon dioxide capture and storage (CCS)	A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage.
Climate change	A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.
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 by: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible (FAO, 2018a).
CO_2 equivalent (CO_2e) emission	The amount of carbon dioxide (CO_2) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for a 100 year time horizon. For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding climate change responses. There is generally no connection between CO2-equivalent emissions and resulting CO_2-equivalent concentrations.
Deforestation	Conversion of forest to non-forest. [Note: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation in the context of reporting and accounting Article 3.3 and 3.4 activities under the Kyoto Protocol, see 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.] See also *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*
Demand and supply-side measures	Demand-side measures: Policies and programmes for influencing the demand for goods and/or services. In the energy sector, demand-side management aims at reducing the demand for electricity and other forms of energy required to deliver energy services. Supply-side measures: Policies and programmes for influencing how a certain demand for goods and/or services is met. In the energy sector, for example, supply-side mitigation measures aim at reducing the amount of greenhouse gas (GHG) emissions emitted per unit of energy produced.
Ecosystem	A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment. See also *Ecosystem services*
Ecosystem services	Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation. See also *Ecosystem*.
Emission factor	A coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions.
Emission scenario	A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gases (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are often used as input to a climate model to compute climate projections. See also *Baseline scenario*, *Mitigation scenario*, *Scenario*.
Food loss and waste	'The decrease in quantity or quality of food'. Food waste is part of food loss and refers to discarding or alternative (non-food) use of food that is safe and nutritious for human consumption along the entire food supply chain, from primary production to end household consumer level. Food waste is recognised as a distinct part of food loss because the drivers that generate it and the solutions to it are different from those of food losses (FAO, 2015b).
Food security	A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life

	(FAO, 2001). [Note: Whilst the term 'food security' explicitly includes nutrition within it 'dietary needs ...for an active and healthy life', in the past the term has sometimes privileged the supply of calories (energy), especially to the hungry. Thus, the term 'food and nutrition security' is often used (with the same definition as food security) to emphasise that the term food covers both energy and nutrition(FAO, 2009).]
Food system	All the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes (HLPE, 2017). [Note: Whilst there is a global food system (encompassing the totality of global production and consumption), each location's food system is unique, being defined by that place's mix of food produced locally, nationally, regionally or globally.]
Forest	A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. [Note: For a discussion of the term forest in the context of National GHG inventories, see the 2006 IPCC Guidelines for National GHG Inventories and information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2019a).] See also *Afforestation*, *Deforestation*, and *Reforestation*.
Global Warming Potential (GWP)	Global Warming Potentials (GWP) are calculated as the ratio of the radiative forcing of one kilogramme greenhouse gas emitted to the atmosphere to that from one kilogramme CO_2 over a period of time (e.g., 100 years).
Governance	A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognises the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community, and the local context where the effectiveness of policies and measures are determined.
Grazing land	The sum of rangelands and pastures not considered as cropland, and subject to livestock grazing or hay production. It includes a wide range of ecosystems, e.g. systems with vegetation that fall below the threshold used in the forest land category, silvo-pastoral systems, as well as natural, managed grasslands and semideserts.
Greenhouse gas (GHG)	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)
Harvested wood products (HWP)	Harvested wood products (HWP) according to the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) and the 2006 IPCC Guidelines refer to wood and paper products, and include i) wood products in use (i.e. wood utilised as a material); ii) wood biomass used for energy purposes and iii) wood biomass in solid waste disposal sites.
Land degradation	A negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans. [Note: This definition applies to forest and non-forest land. Changes in land condition resulting solely from natural processes (such as volcanic eruptions) are not considered to be land degradation. Reduction of biological productivity or ecological integrity or value to humans can constitute degradation, but any one of these changes need not necessarily be considered degradation.]
Land use	The total of arrangements, activities and inputs applied to a parcel of land. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national GHG inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetlands, settlements, other lands (see the 2006 IPCC Guidelines for National GHG Inventories for details).
Land use, land-use change and forestry (LULUCF)	In the context of national greenhouse gas (GHG) inventories under the United Nations Framework Convention on Climate Change (UNFCCC, 2019a), LULUCF is a GHG inventory sector that covers anthropogenic emissions and removal of GHG in managed lands, excluding non- CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e., 'where human interventions and practices have been applied to perform production, ecological or social functions'. Since managed land may include carbon dioxide (CO_2) removals not considered as 'anthropogenic' in some of the scientific literature assessed in this report (e.g., removals associated with CO_2 fertilisation and N deposition), the land-related net GHG emission estimates from global models included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories.
Mitigation (of climate change)	A human intervention to reduce emissions or enhance the sinks of greenhouse gases.
Mitigation scenario	A plausible description of the future that describes how the (studied) system responds to the implementation of mitigation policies and measures.
Nitrous oxide (N_2O)	One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol. The main anthropogenic source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced

	naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.
Peat and Peatland	Soft, porous or compressed, sedentary deposit of which a substantial portion is partly decomposed plant material with high water content in the natural state (up to about 90 percent) (IPCC, 2013a). Peatland is a land where soils are dominated by peat.
Reducing Emissions from Deforestation and Forest Degradation (REDD+)	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 (see UNFCCC decision 1/CP.16, para. 70).
Reforestation	Conversion to forest of land that has previously contained forests but that has been converted to some other use. [Note: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation in the context of reporting and accounting Article 3.3 and 3.4 activities under the Kyoto Protocol, see 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.] See also *Afforestation*, *Deforestation*, and *Reducing Emissions from Deforestation and Forest Degradation (REDD+).*
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions. See also *Baseline scenario*, *Emission scenario*.
Soil organic matter (SOM)	The organic component of soil, comprising plant and animal residue at various stages of decomposition, and soil organisms.
Sustainable intensification (of agriculture)	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).]
Sustainable land management	The stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions (Adapted from WOCAT, undated).
Tier	In the context of the IPCC Guidelines for National Greenhouse Gas Inventories, a tier represents a level of methodological complexity. Usually three tiers are provided. Tier 1 is the basic method, Tier 2 intermediate and Tier 3 most demanding in terms of complexity and data requirements. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate.
Wetland	Land that is covered or saturated by water for all or part of the year (e.g., peatland).

Source: (IPCC, 2006a)

Acronyms

AFOLU	Agriculture, Forestry and Other Land Uses
BAU	Business as Usual
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
CSA	Climate Smart Agriculture
ETF	Enhanced Transparency Framework
FOLU	Forestry and Other Land Uses
GHG	Greenhouse Gas
GWP	Global Warming Potential
HWP	Harvested Wood Products
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
MPG	Modalities, Procedures and Guidelines
NDC	Nationally Determined Contribution
NGHGI	National Greenhouse Gas Inventory
NIR	National Inventory Report
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous Oxide
REDD+	Reduced Deforestation and Forest Degradation
SDG	Sustainable Development Goal
SOM	Soil Organic Matter
UNFCCC	United Nations Framework Convention on Climate Change

Executive summary

The present working paper informs policymakers and technical experts at national and subnational levels involved with the UNFCCC process about the opportunities for and challenges related to climate change mitigation in the agriculture, forestry and other land uses (AFOLU) sector. This chapter summarizes key messages from this working paper.

Mitigation in the AFOLU sector is critical to achieving the Paris Agreement goals

Both mitigation and adaptation are equally important to reaching the Paris Agreement's temperature goal and its global goal on adaptation. The AFOLU sector contributes nearly a quarter of global annual anthropogenic GHG emissions. Emission sources are primarily related to N_2O and CH_4 from agricultural production and CO_2 from land use, land-use change, and forestry. Important mitigation options arise for all land categories, both through reduction of emissions and the enhancement of removals. At the same time the AFOLU sector is highly vulnerable to climate impacts, such as through floods and droughts, which are expected to grow as climate change progresses, in particular beyond 1.5°C above pre-industrial levels. This is expected to have effects on all aspects of food security and will also impact health, water security, ecosystem services, and biodiversity, among others. Adapting to current and future climate change is therefore a necessity even if strong mitigation can avert the worst impacts.

GHG emissions from the AFOLU sector are rising due to growing demands, but there are large mitigation potentials. Current annual anthropogenic GHG emissions in the AFOLU sector amount to 12.0 ± 2.9 Gt CO_2e. Meeting the growing demands for food, feed, fibres, and fuel without mitigation would add about 3 Gt CO_2e by 2050, resulting in AFOLU related GHG emissions of ca. 15 Gt CO_2e by 2050. The IPCC's AR5 estimated an economic mitigation potential (at US$ 100) of 7.2-10.6 Gt CO_2e per year by 2030, and others have estimated mitigation potentials of between 10 and 15 Gt CO_2e per year. This suggests that there is a large potential for the AFOLU sector to contribute to achieving the Paris Agreement's stabilization temperature goal of "well below 2°C above pre-industrial levels".

Mitigation in the AFOLU sector can take place in all major land-uses and can have multiple co-benefits

Emissions are nearly evenly split between agriculture on the one hand and forestry and other land uses on the other and result from different processes and sources. Agriculture is responsible for just over 50% of AFOLU emissions. Methane producing enteric fermentation from livestock is responsible for ca. 40% of agricultural emissions. Rice cultivation and manure management add 10% and 7% to overall emissions, respectively, predominantly from CH_4 but also from N_2O. Emissions from all fertilizer categories applied to soils combined make up 36%, mainly form manure and synthetic fertilizers. The remaining emissions come from organic soils and biomass burning. Forestry and other land uses are responsible for just under 50% of AFOLU emissions, mainly as CO_2. Conversion of forest land is responsible for nearly 60% of all FOLU emissions. Biomass burning contributes about a quarter of FOLU emissions, and emissions from drained peat soils add 16%.

Mitigation in agriculture is achieved through measures that both reduce emissions from crop and livestock systems and enhance sinks such as improved soil management and additional biomass. Emissions reduction in agriculture can be achieved in all subsectors through a wide range of measures. In **livestock** systems, feeding, feed supplements, improved animal welfare, and breeding can enhance productivity while influencing ruminant methanogenesis can lower CH_4 emissions directly. Mitigation options from **manure management** aim to reduce CH_4 and N_2O emissions through improved manure storage and deposition, anaerobic digestion, and changes in feed and grazing practices. In **rice** systems, mitigation options include improving water and residue management as well as improved fertilizer practices. Options to reduce N_2O emissions from the application of **synthetic fertilizers** and **manure** to soils largely rely on improving fertilizer management through application delivery, rates and timing, fertilizer types, and nitrification inhibitors. Options to reduce N_2O emissions from manure left on pastures include reducing grazing activity to manage manure in more controlled environments and improving livestock performance. Mitigation of N_2O emissions from **crop residues** can be realized through better water and tillage management as well as improved fertilizer practices. Options to reduce N_2O (CO_2 under FOLU) emissions from the **cultivation of organic soils** include reducing their use in agriculture, which produces a wide range of ecosystem services and biodiversity benefits, and enhancing productivity through improved nutrient, water, and soil management. Options to abate CH_4 and N_2O emissions from **burning savannah** biomass (CO_2 reductions reported under FOLU) are different forms of management to prevent, control, and restrict fires, prescribed burning, and management of fire regimes, whereas **burning crop residues** can be reduced via regulation and incentives for better soil management.

Mitigation on forest land is achieved primarily by reducing deforestation and forest degradation (REDD+) and by enhancing terrestrial carbon stocks. Reducing tree cover loss and disturbance to conserve the existing carbon pool requires controlling the drivers of deforestation, such as agriculture, mining, or infrastructure, and of forest degradation, including overharvesting, poor harvesting practices, pests and diseases, and wildfires. This can be achieved by a range of actions including the establishment of protected areas, improving law enforcement, establishing forest moratoria, improving forest governance and tenure arrangements, supporting community forest management, and commodity roundtables, among others. Afforestation and reforestation enhance both biomass and soil organic matter on unforested land by planting trees, whereas forest restoration relies on a more ecologically integrated form of planting trees, natural succession processes, and a number of instruments to protect forests from drivers of degradation and enhance their resilience against a range of shocks. If well planned, all these activities can lead to multiple co-benefits, including improved ecosystem services and greater biodiversity.

Mitigation on all/other land uses is achieved by enhancing carbon through restoration of degraded ecosystems or by avoiding carbon losses through protective measures. Restoration of peatland by abandoning its use for crops or livestock can strongly reduce GHG emissions arising from the mineralization of carbon in organic soils due to high carbon stocks on a comparatively small scale. Similarly, mitigation benefits can be achieved by restoring degraded wetlands, including mangroves, saltmarshes, and seagrass meadows. Protecting other land uses, particularly natural ecosystems high in terrestrial carbon that also provide ecosystem services and biodiversity, from conversion can also contribute effectively to mitigation. In all cases it is important to remove the drivers of degradation and land-use change.

Integrated mitigation options can provide important benefits for adaptation, ecosystem services, biodiversity, livelihoods, and health. If well executed, integrated mitigation options can lead to multiple co-benefits for ecosystem services, biodiversity, and resilience against climate shocks, as well as opportunities for jobs and livelihoods. Integrated options in agriculture include, among others, enhancing productivity through improved cropland, grazing land, and livestock management, as well as agroforestry. Besides avoiding emissions and enhancing soil organic matter and biomass, these measures can reduce pressures for conversion and degradation on forests and other land uses. Reducing deforestation and forest degradation as well as protecting other natural and semi-natural ecosystems from destruction and degradation can provide important ecosystem services, flood control, and biodiversity benefits. Restoration of degraded forests, grasslands, peatlands, and coastal wetlands can increase system resilience through improved ecosystem services and allows biodiversity to recover while offering opportunities for livelihoods. Different forms of fire management not only protect lives and assets but also contribute significantly to GHG mitigation and respiratory health impacts from avoided smoke and air pollution.

Mitigation in the AFOLU sector takes place in the context of other land challenges

Considering other demands to land and ecosystem sustainability when planning mitigation in the AFOLU sector allows to address multiple SDGs. Many mitigation options can also provide significant benefits for system resilience, ecosystem services, biodiversity, and livelihoods. At the same time, there are growing demands to meet food, water, and energy security, among others, all of which compete for limited land resources. Implementation of mitigation options should consider such larger perspectives and focus on maximising welfare and synergies to benefit from the limited land resources. Considering these interactions when planning mitigation in the AFOLU sector also addresses several of the United Nations Sustainable Development Goals, notably SDG 2 (food security), SDG 6 (water), SDG 7 (energy), SDG 13 (climate), and SDG 15 (natural environment), as well as potentially others, such as goals related to justice and governance.

Policy coherence and integration across relevant sectors and levels of governance are important to achieve mitigation benefits while minimizing trade-offs. Achieving mitigation outcomes in a context as complex as the AFOLU sector can lead to significant trade-offs. To minimize possible trade-offs of mitigation efforts, benefits should be considered in the context of all possible risks. Typically, greater integration and policy coherence across sectors and levels of governance enhance the ability to address the multiple demands to land. Achieving mitigation outcomes thus requires creating conditions that enable greater policy coherence, including through learning and changing of values and mindsets.

National GHG inventories are critical to AFOLU sector mitigation.

National GHG inventories are important tools to identify emission sources, monitor progress towards mitigation targets, and support decision-making. National GHG inventories account for a country's GHG emissions and removals and are therefore a key tool to identify major emission sources and areas of concern, monitor the progress towards a mitigation target, and support political decision-making. National GHG inventories are based on a set of rules and methodologies to capture GHG sources and sinks related to actions in the AFOLU sector in a structurally coherent and comprehensive way to report all major emissions and removals and avoid double counting. Based on their structure, NGHGIs offer a rear-view perspective of changes in the AFOLU sector between earlier inventories and the latest one. Over time this allows to identify trends that can be extrapolated to provide baselines of expected future developments. Mitigation strategies can then be devised through measures that diverge from the baseline.

Data availability and accuracy are the strongest limitations affecting land representation and consequently the GHG inventory results. In the AFOLU sector, a greater stratification of land use categories will improve the quality of the inventory, in particular if it is complemented with country-specific emission factors. The IPCC therefore recommends using generic emission factors (tier 1) only where alternatives are not accessible. While it is possible to represent most GHG emissions and removals with country-specific emission factors (tier 2), specifically in combination with a sufficiently high number of land-use categories. However, more sophisticated approaches, such as process-based models and full spatial and temporal representation, may be needed for some cases even though, such approaches and methods are typically more data and capacity intensive and may not be available.

1 Introduction

This working paper is meant to inform policymakers and technical experts at national and subnational levels about the opportunities for and challenges related to climate change mitigation in the agriculture, forestry and other land uses (AFOLU) sector. It also provides relevant information regarding monitoring and reporting of greenhouse gas (GHG) emissions and removals and the development of baselines in national GHG inventories.

The working paper first provides an overview of greenhouse gas (GHG) emissions and removals in the AFOLU sector, followed by descriptions of relevant mitigation measures that are based primarily on the IPCC's Special Report on Climate Change and Land (IPCC, 2019). Considering the AFOLU sector's complex interactions with other sectors and areas of concern, such as food security, water, energy, and the preservation of intact natural systems to support the long-term provisioning capacity of ecosystem services, the paper then discusses mitigation strategies and measures that meet criteria for long-term sustainability and national development and ways through which to address them. It then offers an overview of developing GHG inventories and baselines in the AFOLU sector in order to report progress on mitigation based on the IPCC's 2006 national GHG inventory (NGHGI) guidelines (IPCC, 2006). Concluding, the paper provides a number of key messages and recommendations.

1.1 Relevance of the AFOLU sector to reaching the Paris Agreement goals

The AFOLU sector is critical to reaching the Paris Agreement goals as it contributes nearly a quarter of global annual anthropogenic GHG emissions in the form of CO_2, CH_4, and N_2O while at the same time being highly vulnerable to the impacts of climate change (IPCC, 2019b). Mitigation and adaptation are hence equally important to reaching the Paris Agreement's temperature goal and its global goal on adaptation (UNFCCC, 2016).

The AFOLU sector's vulnerability to climate-related impacts, such as droughts and floods, is already very high and is expected to grow as climate change progresses, in particular beyond 1.5°C above pre-industrial levels (Hoegh-Guldberg *et al.*, 2018; Jia *et al.*, 2019). Many vulnerable ecosystems and population groups are already negatively affected by climate impacts, and climate risks to ecosystems and humans will rise as climate change accelerates and increasingly more systems will reach limits of adaptation (Hoegh-Guldberg *et al.*, 2018).

New evidence contends that unmitigated climate change may push a third of global food production beyond temperature, precipitation, and aridity levels conducive to agricultural production by the end of the century, the most vulnerable regions being south and southeast Asia and Africa's Sudano-Sahelian zone (Kummu *et al.*, 2021). Hence, the smaller the change in temperature above pre-industrial levels the less likely will it be for natural and managed ecosystems to be negatively affected. Nevertheless, even with strong mitigation, net food production is expected to be negatively affected despite some regions initially experiencing an increase in productivity (Porter *et al.*, 2014; WRI, 2019).

There is high confidence that future climate change will negatively affect all aspects of food security (availability, access, utilization, stability), leading to complex impacts depending on regional and development-related characteristics with smallholder farmers and other vulnerable population groups specifically at risk (Mbow *et al.*, 2019; Kummu *et al.*, 2021). This is also expected to have growing effects on climate- and food-related health risks (Phalkey *et al.*, 2018). Climate-related changes in food supply, water security, forest extent or quality, and frequency of fire, could also lead to a rise in conflicts, both domestic and regional, and result in a rise of migration and internal displacement (Abbott *et al.*, 2017; de Amorim *et al.*, 2018; Froese *et al.*, 2019; Verschuur *et al.*, 2021)

Current annual anthropogenic GHG emissions in the AFOLU sector amount to 12.0 ± 2.9 Gt CO_2e, i.e., approximately 23% of the global total (Jia *et al.*, 2019). Emission sources are primarily related to N_2O and CH_4 from agricultural production and CO_2 from land use, land-use change, and forestry. Meeting the growing demands for food, feed, fibres, and fuel would add about 3 Gt CO_2e by 2050, resulting in AFOLU related GHG emissions of ca. 15 Gt CO_2e by 2050 under a business-as-usual scenario (Jia *et al.*, 2019). The IPCC's AR5 estimated an economic mitigation potential (at US$ 100) of 7.2-10.6 Gt CO_2-eq. per year by 2030. Smith *et al.* (2014), and Roe *et al.* (2019) recently estimated the mitigation potential of improvements in the land-use sector to be 10-15 Gt CO_2e yr^{-1}. Hence, there is considerable potential for the AFOLU sector to contribute to achieving the Paris Agreement's stabilization temperature goal of "well below 2°C above pre-industrial levels".

Given how external drivers affect both the emissions from the AFOLU sector and its future vulnerability to climate impacts, this working paper also looks at broader land-related issues that shape the sector's interactions with a range of demands for increasingly scarce and finite natural resources. Globally, ice-free land surfaces comprise 130 million km^2 of which only 28% are not used for human purposes (Arneth *et al.*, 2019; Figure 1.1). The current distribution between managed and unmanaged lands is the result of centuries-long transformations of natural ecosystems to meet growing human demands for food, feed, fibres, and other ecosystem products. According to a recent analysis, global land use changes have affected almost a third (32%) of global land area in just six decades, which is about four times the extent of previous assessments (Winkler *et al.*, 2021). As the global population grows to a projected 9.8 billion in 2050, overall food demand is expected to rise by more than 50%, and demand for animal-based foods is expected to increase by nearly 70%, mainly due to dietary shifts connected to rising affluence in developing countries (WRI, 2019). At the same time, demands for other ecosystem products, such as wood and biofuels, are also growing in the context of a booming bioeconomy and thus adding to the pressures on land (Fritsche *et al.*, 2020). To meet these increasing demands, the World Resources Institute estimates that under a business-as-usual trajectory about 6 million km^2 of land will need to be converted to some form of management, one third of which would be for cropland (WRI, 2019).

This complex interrelationship between climate vulnerability, contribution to climate change, and the need to increase production in the wake of strong underlying drivers places the AFOLU sector at the centre of both a wide range of current and growing challenges and their solutions.

Given global climate policy targets and the AFOLU sector's vulnerability to climate impacts, deep transformational change leading to strong mitigation outcomes across all sectors is clearly the most urgent action to minimize future climate change (Hoegh-Guldberg *et al.*, 2018) . In many circumstances this can be achieved through measures that provide adaptation and food security co-benefits and thus also limits
resource constraints and the impacts of future climate change on the AFOLU sector. Many of these options can also enhance system resilience to climate shocks while concomitantly improving food security and contributing to mitigation in the AFOLU sector. For instance, Smith *et al.*, (2019) provide a long list of integrated l and management options, most of which have significant benefits for all five land challenges (degradation, desertification, food security, mitigation, and adaptation) described in the IPCC Special Report on Climate Change and Land (IPCC, 2019b). From this list, 15 supply-side options related to AFOLU were selected for this working paper based on their contribution to mitigation and are discussed in the context of their mitigation benefits as well as

other benefits, such as food security, adaptation, and contribution to biodiversity (Smith *et al.*, 2019; Pörtner *et al.*, 2021). Demand-side mitigation options and measures related to the wider food system, while critical to achieving the Paris Agreement goals, are not discussed in this publication because their GHG emissions and removals are reported under other sections of the NGHGI.

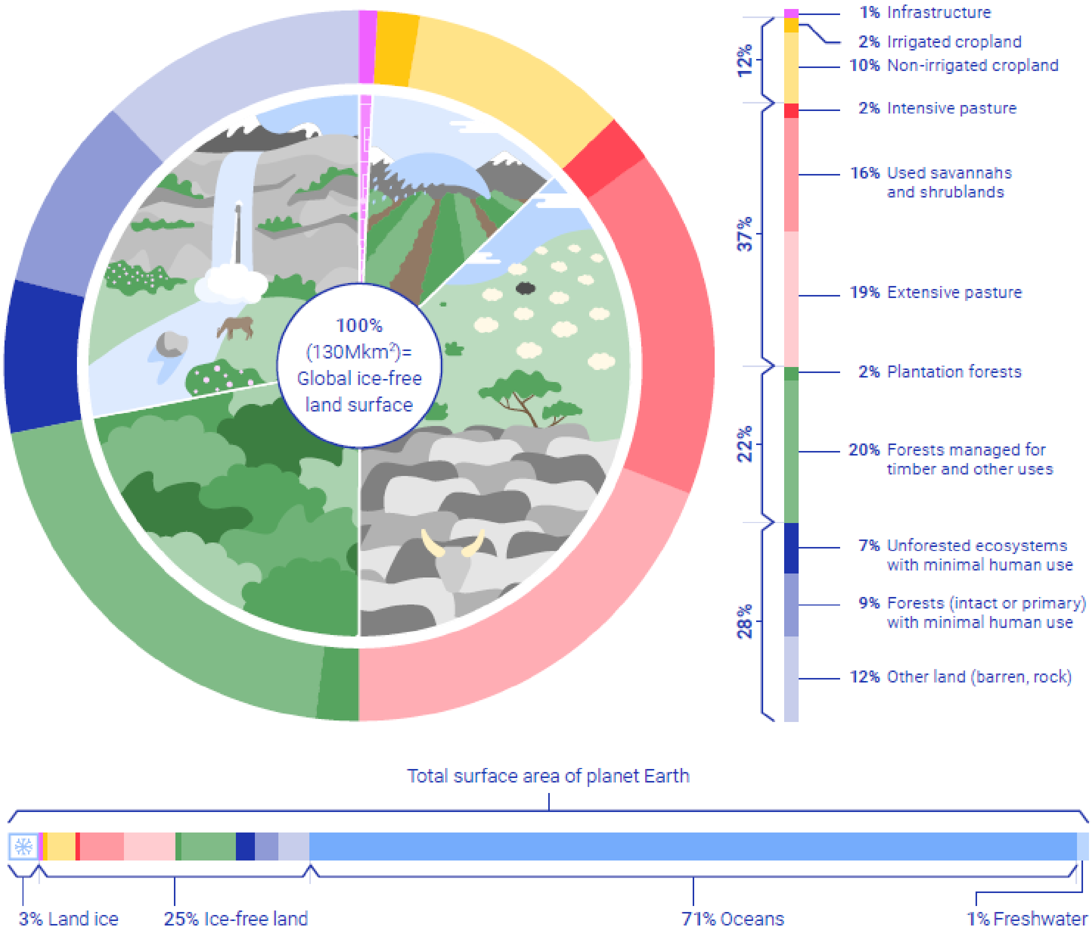

Figure 1.1. Global use of ice-free land around year 2015 for different categories of use ordered by decreasing land-use intensity clockwise from the top (UNEP, 2021). 1.2 Opportunities and challenges for mitigation within the AFOLU sector

When planning for mitigation options in the AFOLU sector, other considerations besides productivity and resilience need to be taken into account. The AFOLU sector cannot be seen in isolation because of strong interactions with other demands on land, for instance related to water and energy security, as well as other sectors, such as infrastructure or urban planning. In addition, the long-term sustainability of the environmental systems underpinning the regulating, supporting, provisioning, and cultural ecosystem services all our lives depend on must be ensured (e.g., Seppelt *et al.*, 2013; Newbold *et al.*, 2016; Campbell *et al.*, 2017; Conijn *et al.*, 2018; Soto Golcher and Visseren-Hamakers, 2018; Springmann *et al.*, 2018; Melo *et al.*, 2020). While the interactions can be synergistic, neutral, or in the form of trade-offs, their appropriate integration at different spatial and temporal scales during planning and implementation of interventions can often minimize trade-offs in connected sectors and improve long-term sustainability (Kurian, 2017; Liu *et al.*, 2018; Mercure *et al.*, 2019; Xu *et al.*, 2019; Melo *et al.*, 2020). Considering these interactions when planning interventions in the AFOLU sector also addresses several of the United Nations Sustainable Development Goals, notably SDG 2 (food security), SDG 6 (water), SDG 7 (energy), SDG 13 (climate), and SDG 15 (natural environment), as well as potentially others, such as goals related to justice and governance, etc.(Pradhan *et al.*, 2017; Leal Filho *et al.*, 2020). However, despite the many benefits, integration across sectors can be difficult to achieve due to governance-related challenges and system inertia (Leck *et al.*, 2015; Weitz *et al.*, 2017; Wichelns, 2017). Issues pertaining to decision-making and managing the inherent complexities within the AFOLU sector are therefore also discussed.

1.3 Reporting GHG emissions and removals in the AFOLU sector

In addition to contributing to a better understanding of the broader issues within which mitigation in the AFOLU sector can take place, an important element of this publication is to provide an overview of approaches and methods for GHG reporting in the AFOLU sector. Reporting of GHG emissions and removals in the context of the UNFCCC takes place via national inventory reports (NIRs), which are mandatory under the rules laid out in the modalities, procedures and guidelines (MPGs) to implement the Enhanced Transparency Framework (ETF). The NIRs are currently based on the 2006 IPCC guidelines for national GHG inventories (NGHGIs) in the AFOLU sector as well as the 2013 supplement for wetlands (IPCC, 2006b, 2014; UNFCCC, 2018). These guidelines for NGHGIs describe approaches to developing national inventory frameworks and provide detailed instructions how to account for GHG source and sink categories relevant to the AFOLU sector.

By definition, reporting GHG emissions and removals via an inventory approach is achieved by comparing GHG source and sink categories through repeated assessments. Over time it is then possible to identify trends in emissions and removals from the different categories and thus determine whether or not the AFOLU sector has contributed to GHG emission reduction targets compared to the baseline. To address differences in capacities and data availability, inventories combine either emission factors and activity data for each of the land categories (tiers 1 and 2), or they utilize typically more sophisticated approaches (e.g., statistical or process-based models) to account for GHG flows (tier 3). Figure 1.2 gives a schematic overview of the main GHG source and sink categories in managed ecosystems, while unmanaged ecosystems only appear in the NGHGI if there is a change in terrestrial carbon stocks leading to increased emissions or removals. Both the main sink and source categories in the AFOLU sector and approaches to reporting actions relevant to these categories in the NGHGI are described in this document.

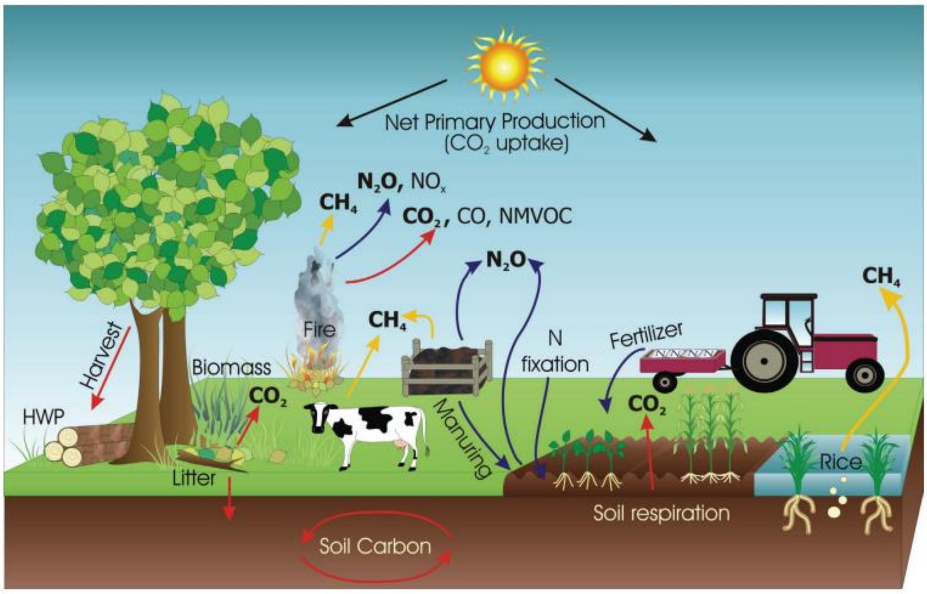

Figure 1.2: The main greenhouse gas sources/sinks and underlying processes in managed ecosystems (IPCC, 2006a).

2 GHG sources and sinks and mitigation options in the AFOLU sector

This chapter first provides a summary of GHG emissions and removals in the AFOLU sector, broken down by gases and key source and sink categories. The characterization of GHG emissions and removals follows (FAO, 2016) and Tubiello *et al.* (2014), both of which are based on FAOSTAT data. The chapter then presents a range of mitigation options in the AFOLU sector. Mitigation options are described based on information provided in the IPCC Special Report on Climate Change and Land (Smith *et al.*, 2019). The chapter concludes with an example how to identify and select specific mitigation actions in the AFOLU sector.

Mitigation options focus on supply-side measures and provide information on how to report emissions and removals in the NGHGI. Demand-side measures and measures related to the food system, while important, are not addressed in the context of this document as they are typically not directly relevant to the AFOLU sector. Mitigation options focusing on the provision of bioenergy are likewise not taken into account because only the land-related emissions and removals are reported under AFOLU whereas the energy-related avoided emissions are reported under energy in the NGHGI.

2.1 GHG emissions and removals in the AFOLU sector

Agriculture, forestry, and other land uses (AFOLU) are a significant source of GHG emissions, responsible for about 23% of total net anthropogenic GHG emissions (Jia *et al.*, 2019). At the same time, the AFOLU sector is an important sink for CO_2, contributing strongly to the removal of GHGs from the atmosphere (Jia *et al.*, 2019). Between 2007 and 2016 the AFOLU sector emitted 12.0 ± 2.9 Gt CO_2e yr^{-1} (Table 2.1). Emissions from the AFOLU sector are predominantly in the form of CO_2, CH_4, and N_2O[1] and are nearly evenly split between agricultural production with 12% and land use, land-use change, and forestry (LULUCF; equivalent to FOLU) with 11%. Emissions and removals can be disaggregated further by their source and sink categories, i.e., the processes and subsystems within the AFOLU sector through which the different GHGs are emitted into or removed from the atmosphere.

2.1.1 Disaggregation of GHG emissions by source gases

Net CO_2 emissions from the AFOLU sector are 5.2 ± 2.6 Gt CO_2 yr^{-1} and make up roughly 13% of global anthropogenic CO_2 emissions (Jia *et al.*, 2019). They are the result of two opposing fluxes: 1) gross emissions of around 20 Gt CO_2 yr^{-1} from deforestation, cultivation of soils, and mineralization of wood products and other sources of biogenic carbon, such as through peatland drainage and burning; and 2) gross removals of around -14 Gt CO_2 yr^{-1}, largely from forest regrowth and agricultural abandonment (Le Quéré *et al.*, 2018).

In addition to anthropogenic fluxes, there is a natural response to human-induced environmental changes due to higher CO_2 concentrations, nitrogen deposition, and climate change, resulting in a

[1] All emissions are subsequently presented in the form of CO_2 equivalents (CO_2e) in order to compare the different gases with each other. Global warming potentials (GWPs) to convert CH_4 and N_2O into CO_2e are 28 and 265, respectively, and based on AR5's 100-year warming potentials (IPCC, 2014). Given the short half-life of methane (CH_4) in the atmosphere, its GWP is 84-86 times stronger than CO_2 over 20 years (IPCC, 2013b). Prioritizing CH_4 abatement as early mitigation options (e.g., from enteric fermentation, rice, or manure) would therefore have stronger mitigation effects than the inventory suggests.

removal of 11.2 ± 2.6 Gt CO_2 yr^{-1} from the atmosphere, such that the net land-atmosphere flux is currently -6.0 ± 3.7 Gt CO_2 yr^{-1} (Table 2.1). While this removal is currently increasing, there is no guarantee that the trend will continue, and stabilizing and ultimately reducing GHG concentrations in the atmosphere will eventually reverse the signal thereby weakening the mitigation effects (Le Quéré *et al.*, 2018).

Table 2.1 1Net anthropogenic emissions due to Agriculture, Forestry, and other Land Use (AFOLU) and non-AFOLU (average for 2007–2016)1. Positive values represent emissions; negative values represent removals (Jia et al., 2019)

Direct anthropogenic									
Gas	Units	Net anthropogenic emissions due to Agriculture, Forestry, and Other Land Use (AFOLU)			Non-AFOLU anthropogenic GHG emissions[4]	Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions by gas	Natural response of land to human-induced environmental change[5]	Net land-atmosphere flux from all lands
		FOLU	Agriculture	Total					
		A	B	C = A + B	D	E = C + D	F = (C/E) x 100	G	A+G
CO_2[2]	GtCO_2 yr^{-1}	5.2 ± 2.6	No data	5.2 ± 2.6	33.9 ± 1.8	39.1 ± 3.2	13%	-11.2 ± 2.6	-6.0 ± 3.7
CH_4[3,6]	MtCH_4 yr^{-1}	19.2 ± 5.8	141.6 ± 42	160.8 ± 43	201.3 ± 100.6	362 ± 109			
	GtCO_2-eq yr^{-1}	0.5 ± 0.2	4.0 ± 1.2	4.5 ± 1.2	5.6 ± 2.8	10.1 ± 3.1	44%		
N_2O[3,6]	MtN_2O yr^{-1}	0.3 ± 0.1	8.3 ± 2.5	8.7 ± 2.5	2.0 ± 1.0	10.6 ± 2.7			
	GtCO_2-eq yr^{-1}	0.09 ± 0.03	2.2 ± 0.7	2.3 ± 0.7	0.5 ± 0.3	2.8 ± 0.7	81%		
Total (GHG)	GtCO_2-eq yr^{-1}	5.8 ± 2.6	6.2 ± 1.4	12.0 ± 2.9	40.0 ± 3.4	52.0 ± 4.5	23%		

[1] Estimates are only given until 2016 as this is the latest date when data are available for all gases.
[2] Net anthropogenic flux of CO_2 due to land cover change such as deforestation and afforestation, and land management including wood harvest and regrowth, as well as peatland burning, based on two bookkeeping models as used in the Global Carbon Budget and for AR5. Agricultural soil carbon stock change under the same land use is not considered in these models.
[3] Estimates show the mean and assessed uncertainty of two databases, FAOSTAT and USEPA 2012.
[4] Total non-AFOLU emissions were calculated as 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.
[5] The natural response of land to human-induced environmental changes is the response of vegetation and soils to environmental changes such as the increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change. The estimate shown represent the average from Dynamic Global Vegetation Models.
[6] All values expressed in units of CO_2-eq are based on AR5 100-year Global Warming Potential (GWP) values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28). Note that the GWP has been used across fossil fuel and biogenic sources of methane. If a higher GWP for fossil fuel CH_4 (30 per AR5), then the total anthropogenic CH_4 emissions expressed in CO_2-eq would be 2% greater.

CH_4 emissions from the AFOLU sector amount to the equivalent of 4.5 ± 1.2 Gt CO_2e yr^{-1}, which corresponds to 44% of total anthropogenic CH_4 emissions (Table 2.1). CH_4 accounts for approximately 37% of AFOLU-related emissions, nearly 90% of which result from agriculture, primarily ruminant enteric fermentation, rice cultivation, and manure management (Tubiello *et al.*, 2013; Smith *et al.*, 2014; Grassi *et al.*, 2017) .

Anthropogenic N_2O emissions from the AFOLU sector amount to the equivalent of 2.3 ± 0.7 Gt CO_2e yr^{-1}, which is 81% of the global total. Through this N_2O contributes roughly 19% of all emissions from the sector due to its high global warming potential (GWP). N_2O emissions from the AFOLU sector derive primarily from agricultural production, in particular nitrogen fertilizers, animal droppings, drained peatlands, and manure management, but biomass burning also contributes to the total (Smith *et al.*, 2014).

Without interventions, GHG emissions from agriculture are likely to increase by about 30-40% by 2050 compared to average 2000s levels, largely due to increasing demand based on population and income growth and dietary change, primarily in developing countries (Tubiello *et al.*, 2014; FAO, 2018b; Mbow *et al.*, 2019; WRI, 2019). This increase represents projected GHG emissions from agriculture reaching 8–9 Gt CO_2e yr^{-1} by 2050 (Mbow *et al.*, 2019).Without innovations and technological change continuing to progress at current rates, the increase in emissions could be even higher (Springmann *et al.*, 2018; WRI, 2019).

In addition to the emissions accounted directly under the AFOLU sector, emissions from the use of energy add to the overall GHG burden of the AFOLU sector. Based on data from the IEA, Tubiello *et al.*(2014) estimate that emissions from energy use have risen from 627 Mt CO_2e in the 1990s to 785 Mt CO_2e in 2010, nearly half of which was related to the combustion of diesel, followed by the use of electricity with nearly 40%. Activities beyond the farm gate also contribute substantially to emissions from the food system. The SRCCL attributes 2.6-5.2 Gt CO_2e yr^{-1} to food processing, retail, food wastes, and the production of fertilizers and fuels (Mbow *et al.*, 2019). This adds another 5-10% to the approximately 23% of global GHG emissions related to the AFOLU sector without considering the energy needed for cooking.

2.1.2 Disaggregation of GHG emissions by source categories

Using the FAOSTAT database, Tubiello *et al.* (2014) estimated the GHG emissions and removals in the AFOLU sector by source and sink categories. Differences in the totals between Tubiello *et al.* (2014) and the numbers presented in Table 2.1 are due to the IPCC estimate resulting from a number of different approaches besides the nationally reported inventories reflected in FAOSTAT. The following subsections provide brief descriptions of the emission source categories in the AFOLU sector, focusing on the main gases responsible for the emissions, as well as their historical and regional trends. Though mitigation is discussed in more detail in Section 3.2, options for GHG abatement are also briefly mentioned here in the context of their main source categories.

Between 1990 and 2010, net emissions (emissions minus removals) increased by ca. 8% from 7.5 Gt CO_2e to 8.1 Gt CO_2e (Figure 2.1). This was due to an increase in emissions from agriculture, a decrease in emissions from forests and biomass burning (savannahs and agriculture), and a reduction in forestry removals by more than a third. In 1990, agriculture and forestry contributed both roughly 44% of the total emissions, yet by 2010 agriculture was the largest source of emissions with 53% whereas forest conversion had contracted to 37%. At the same time, the forest sink shrunk by nearly 30%. Regional disaggregation shows that 44% of agricultural emissions come from Asia, followed by the Americas, Africa, and Europe with 25%, 15%, and 12%, respectively, whereas Oceania only contributes with 4%. Current trends indicate rising emissions in Asia, Africa, and the Americas and falling emissions in Europe and Oceania (Tubiello *et al.*, 2014) For emissions from FOLU, the regional distribution is different, with the Americas contributing with over 50%, followed by Africa (26%) and Asia (15%).

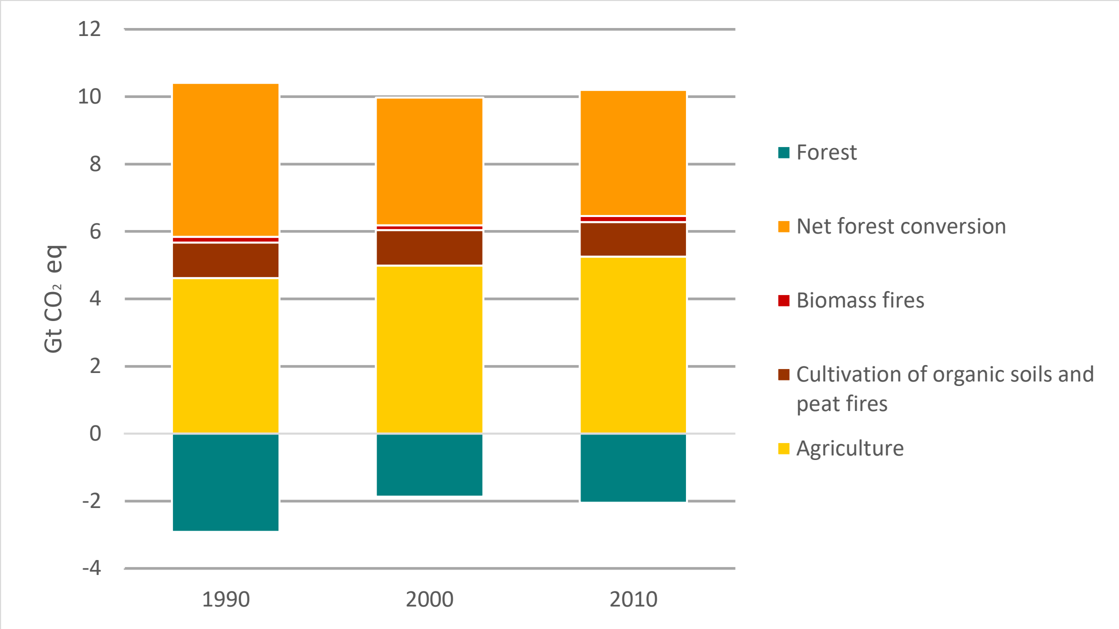

Figure 2.1.Historical trends in AFOLU GHG sources and sinks (Tubiello *et al.*, 2014)

2.1.2.1 Agriculture

Emissions from agriculture are related to livestock, manure, rice, soils (including from synthetic fertilizers, manure applied to arable soils and pastures, and crop residues left on soils), the cultivation of organic soils, and burning of biomass from crop residues and savannas (Figure 2.2). Together, they are responsible for 52% of AFOLU emissions. With 40% of all agricultural emissions, CH_4 produced by ruminant livestock through enteric fermentation is by far the largest single source of GHGs. Combined emissions from all fertilizer categories applied to soils make up 36%, to which manure applied to pastures and synthetic fertilizers contribute with 16% and 13%, respectively, whereas manure and crop residues on agricultural fields only contribute with 4% each. Rice cultivation and manure management add 10% and 7% of all agricultural emissions, respectively, predominantly from CH_4 but also from N_2O. On the other hand, cultivation of organic soils and the burning of biomass are less important as emission sources.

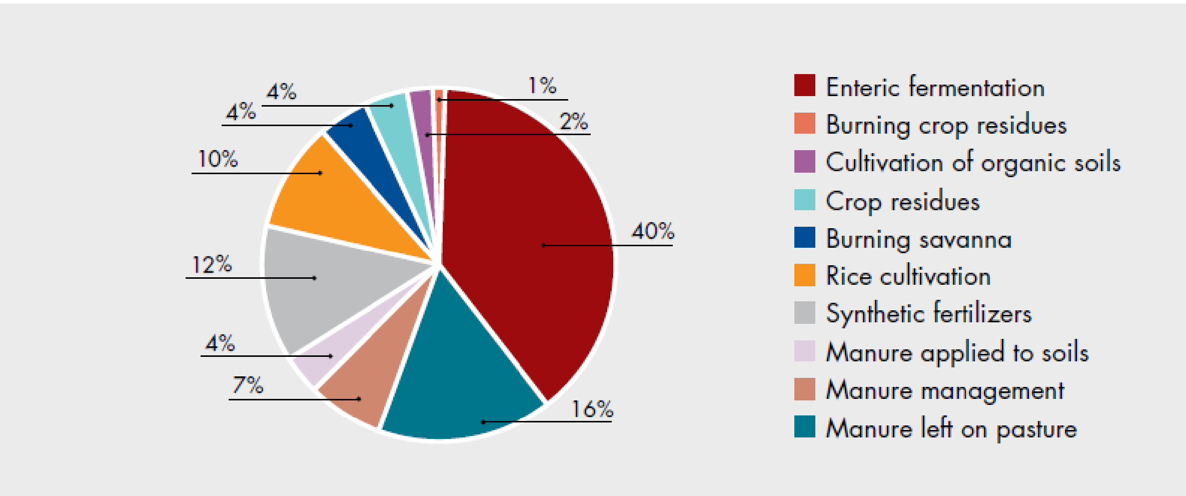

Figure 2.2.Agriculture emissions by subsector, 2001-2011 (FAO, 2016).

Enteric fermentation

Enteric fermentation contributes to agricultural GHG emissions in the form of CH_4 via the digestive systems of ruminant livestock, including cattle, buffaloes, sheep, goats, camels, and llamas, and, to a lesser extent, non-ruminants, including horses, mules, asses, and swine. Global GHG emissions from enteric fermentation were 2,085 Mt CO_2e in 2014 and contribute to agricultural emissions with 40% (FAO, 2016). These emissions are largely dominated by cattle with 74% (55% non-dairy, 18% dairy), while all other ruminants together contribute ca. 24% and non-ruminants produce only ca. 3% of the total (Tubiello *et al.*, 2014). Emissions have been rising at an annual rate of 11% since 1990, mainly due to developing countries´ contributions, whereas emissions from developed countries have been falling. Regionally, Asia (37%) and the Americas (33%) are the largest emitters, followed by Africa, Europe, and Oceania with 14%, 12%, and 4%, respectively (FAO, 2016). Projections suggest that emissions from enteric fermentation will increase by 19% in 2030 and 32% by 2050 compared to a business-as-usual scenario (Tubiello *et al.*, 2014).

Options to reduce the emissions from enteric fermentation can be direct, by influencing ruminant methanogenesis, or indirect, through increases in production efficiency, and include measures related to: 1) feeding; 2) feed supplements and improved health; and 3) breeding (Jia *et al.*, 2019).

Manure management

Manure management contributes to agricultural GHG emissions through aerobic and anaerobic decomposition processes leading to N_2O and CH_4 emissions from livestock (see list under enteric fermentation above and including fowl). Global GHG emissions from manure management were 351 Mt CO_2e in 2014, thus contributing to agricultural emissions with 7% (FAO, 2016). These emissions are dominated by manure from cattle (27% non-dairy, 17% dairy) and swine (28%), followed by chickens (14%) and buffaloes (7%), with all other livestock categories together adding another 7% (Tubiello *et al.*, 2014). Emissions have been rising at an annual rate of 10% since 1990, driven primarily by developing countries, whereas developed countries' emissions have been declining (Tubiello *et al.*, 2014). Asia (43%) is by far the largest emitter, followed by Europe (27%) and the Americas (22%), whereas Africa and Oceania only contribute with 5% and 3%, respectively (FAO, 2016). Compared to average 2000s levels, under the baseline scenario future emissions from manure management are projected to rise by 6% and 47% by 2030 and 2050, respectively (Tubiello *et al.*, 2014).

Mitigation options aim to reduce CH_4 and N_2O emissions from manure storage and deposition and include: 1) anaerobic digestion; 2) the application of nitrification or urease inhibitors; 3) composting; 4) improving practices related to storage and application; 5) changing grazing practices; and 6) modifying feed (Mbow *et al.*, 2019).

Rice cultivation

Rice cultivation emits CH_4 through anaerobic decomposition of organic matter in paddy fields. Global GHG emissions from rice fields were 523 Mt CO_2e in 2014, which corresponds to approximately 10% of total emissions from agriculture and is nearly entirely driven by developing countries, largely from Asia (Tubiello *et al.*, 2014; FAO, 2016). Emissions have been rising at a rate of ca. 8% per year and are expected to reach around 520 Mt CO_2e by 2050 (Tubiello *et al.*, 2014).

Options to reduce the emissions from rice cultivation can be direct, by mitigating CH_4 and N_2O emitting from paddy rice fields, and indirect, through productivity increase, and include: 1) improved water management (e.g., alternative wetting and drying); 2) residue management; and 3) improved fertilizer practices (Mbow *et al.*, 2019).

Synthetic fertilizers

Synthetic fertilizers contribute to agricultural GHG emissions via aerobic and anaerobic pathways leading to N_2O after their application to soils. In 2014, N_2O emissions from synthetic fertilizers were 659 Mt CO_2e, corresponding to about 14% of global emissions (FAO, 2016). While emissions from developed countries have remained largely unchanged between 1990 and 2010, they have nearly doubled to over 500 Mt CO_2e in developing countries over the period (Tubiello *et al.*, 2014). Asia is by far the largest contributor with 63% of global emissions, followed by the Americas (20%) and Europe (13%), while Africa (3%) and Oceania (1%) are negligible (FAO, 2016). Projections under a BAU scenario suggest an increase in emissions by 32% in 2030 and 48% by 2050 compared to average 2000s levels (Tubiello *et al.*, 2014).

Mitigation options to reduce N_2O emissions from the application of synthetic fertilizers largely rely on improving fertilizer management, such as through: 1) improved application delivery; 2) modified rates and timing; 3) optimizing fertilizer types (e.g. slow vs fast release); and 4) using nitrification inhibitors (Smith *et al.*, 2014, 2019).

Manure application to soils

Manure applied to agricultural soils leads to the emission of N_2O by the same processes that result in emissions from synthetic fertilizers (above) and includes manure from the same livestock categories described under manure management (above). Within the subsector, dairy and non-dairy cattle combined contribute 45%, followed by chickens (19%) and swine (18%), with buffaloes, sheep, turkeys, and others together adding 18% to the total (Tubiello *et al.*, 2014). Global emissions were 191 Mt CO_2e in 2014, about 4% of all agricultural GHG emissions, with an annual increment of under 1% between 1990 and 2010, mainly driven by developing countries whereas developed countries have seen a decline over the same period (Tubiello *et al.*, 2014; FAO, 2016). Asia contributes to the total with 45%, followed by Europe and the Americas with 28% and 22%, respectively, whereas Africa (4%) and Oceania (1%) have minor emission burdens (FAO, 2016). Global emissions are expected to grow by 26% in 2030 and 42% in 2050, compared to average 2000s levels, reaching more than 240 Mt CO_2e by the middle of the century (Tubiello *et al.*, 2014) .

Mitigation options are similar to those presented under synthetic fertilizers above, including improved manure application delivery and modified rates and timing (Smith *et al.*, 2014, 2019).

Manure left on pastures

Manure left on pastures by grazing livestock leads to the emission of N_2O by the same processes that result in emissions from synthetic fertilizers (above) and includes manure from the same livestock categories described under manure management (above). Within the subsector, non-dairy cattle contributed over half of all emissions, followed by sheep (12%), goats (12%) and dairy cattle (11%), while all other livestock categories combined contributed 15% of the total (Tubiello *et al.*, 2014). In 2014, global emissions were 845 Mt CO_2e, which is approximately16% of all emissions from agriculture (FAO, 2016). Emissions increased at a rate of 16% per year between 2000 and 2010, which took place entirely in developing countries whereas emissions from developed countries showed a slight decline (Tubiello *et al.*, 2014). The Americas and Asia contributed a third of global emissions each, followed by Africa with a quarter. Europe and Oceania played less prominent roles with 5% and 6%, respectively (FAO, 2016). Projections show that under a BAU scenario emissions will continue to rise strongly and are expected to reach 1,000 Mt CO_2e by 2050, an increase of 40% above average 2000s levels (Tubiello *et al.*, 2014).

Options to reduce N_2O emissions from grazing animal droppings can be achieved by either directly reducing grazing activity, for instance by managing manure in more controlled environments where available, or reduce emission intensity through measures that improve the performance of livestock, such as: 1) grazing land management; 2) feed supplements and improved health; and 3) breeding (Smith *et al.*, 2014; Mbow *et al.*, 2019).

Crop residues

Crop residues contribute to N_2O emissions via nitrification and denitrification processes of the nitrogen contained in plant material left on agricultural fields. Global emissions in 2014 were 212 Mt CO_2e, i.e. about 4% of total emissions from agriculture (FAO, 2016). Residues from crops, wheat (27%), rice (27%), and maize (21%) together made up 75% of total emissions, followed by soybeans (10%), barley (6%), and sorghum (3%). All other crop residue sources combined, including potatoes, millet, dry beans, oats, and rye, led to 6% of emissions (Tubiello *et al.*, 2014). Emissions increased at a rate slightly above 2% per year over the past two decades, primarily from developing countries. Baseline projections suggest continued growth leading to emissions reaching 235 Mt CO_2e in 2050 (Tubiello *et al.*, 2014). From a regional perspective, Asia contributed to global emissions with nearly 50%, followed by the Americas (27%) and Europe (17%), whereas Africa and Oceania showed emissions of 7% and 2%, respectively (FAO, 2016).

Mitigation options to reduce emissions from crop residues are mainly indirect by improving crop productivity through: 1) improved water management; 2) improved fertilizer practices; and 3) tillage management to enhance soil organic matter contents (Smith *et al.*, 2014; Mbow *et al.*, 2019).

Cultivation of organic soils

Drainage of organic soils (also called histosols) from peatlands for agricultural purposes, including cropland (25%) and grassland (75%), leads to both the emission of CO_2, which is more substantive, and of N_2O. However, only the N_2O emissions are addressed within the agriculture sector, whereas the CO_2 emissions are inventoried under FOLU. N_2O emissions from cultivated organic soils add up to 133 Mt CO_2e per year, roughly equally split between developed and developing countries, but flows are constant in the FAOSTAT database over the entire available period so no trends are recorded and no projections can be made(Tubiello *et al.*, 2014; FAO, 2016). Regionally, Asia and Europe contribute the most with 39% and 35%, respectively, followed by the Americas (16%), Africa (6%), and Oceania (4%) (FAO, 2016).

Mitigation options from the cultivation of organic soils involve reducing their use in agriculture through land-use change, which would affect both the N_2O and CO_2 emissions, and indirect options to enhance productivity through improved nutrient, water, and soil management (Smith *et al.*, 2014). Peatland restoration would also entail a wide range of environmental co-benefits, such as water purification and buffering of water flows, as well as large positive effects on biodiversity.

On the other hand, rewetting drained peatlands could enhance CH_4 emissions, partially offsetting the mitigation benefits from avoided histosol subsidence (Smith *et al.*, 2019; Seddon *et al.*, 2020; Pörtner *et al.*, 2021).

Burning savanna

Burning of biomass on savannas used for agricultural purposes, including grasslands, open and closed shrublands, savannas *sensu strictu*, and woody savannas, leads to the release of CH_4 and N_2O and in 2014 resulted in the emission of 213 Mt CO_2e, about 4% of the total, approximately 80% of which originated from developing countries (Tubiello *et al.*, 2014; FAO, 2016). Roughly three quarters of the emissions can be attributed to savannas (39%) and woody savannas (36%), while open shrubland (14%), grassland (9%), and closed shrubland (3%) make up the rest (Tubiello *et al.*, 2014). Emissions fluctuated significantly over the past 20 years, but do not show clear trends and this is expected to continue until 2050 as well (Tubiello *et al.*, 2014). Regionally, emissions are strongly dominated by Africa with 70% of the total, followed by Oceania with 19% and the Americas with 7%, whereas emissions from Asia (3%) and Europe (1%) are minor (Tubiello *et al.*, 2014).

The main mitigation options to abate emissions from savanna biomass burning are different forms of fire management, which target safeguarding lives and assets through preventive, controlling, and restricting measures, but also include prescribed burning and management of fire regimes (Smith *et al.*, 2019; Cochrane *et al.*, 2021). Besides GHG mitigation, these measures provide large benefits related to air pollution, the prevention of soil erosion and land degradation, and the conservation of biological diversity (Pörtner *et al.*, 2021).

Burning crop residues

Similar to the burning of savannas, burning crop residues on agricultural fields leads to CH_4 and N_2O emissions. Nearly half of these emissions originate from maize, while wheat and rice contribute with 25% each, and sugar cane adds the remaining 4%. With a global total of 30 Mt CO_2e, this emission source contributes to agricultural GHG emissions with merely 0.6%, roughly two thirds of which derive from developing countries (Tubiello *et al.*, 2014). Half of all emissions come from Asia, a quarter from the Americas, and Africa and Europe contribute with 11% each, with Oceania adding 2% (FAO, 2016).

Mitigation options to reduce the burning of crop residues would be measures that provide added value to the residues, such as combustion for energy generation or composting, in order to give incentives to stop clearing the land with fire, a practice that involves minimal effort while adding valuable nutrients to the soils (Pörtner *et al.*, 2021). Another way to reduce burning could be via regulation, though the effectiveness would depend on enforcement.

Box 2.1. The European Union's main mitigation strategies in the AFOLU sector.
At EU level, the successive editions of the Climate and Energy Package (CEP) have set the general targets and the framework for GHG mitigation actions for each 10-years period. The current CEP covering the period 2020-2030 foresees a minimum 40% reduction in GHG emissions by 2030 compared to 1990 levels, which is in line with the Paris Agreement (EC, 2014).

Despite its relevance (in 2018 the agricultural sector accounted for 10% of all GHG emissions in the EU, while LULUCF was a net carbon sink (Mandl *et al.*, 2020)), the first CEP (2010-2020) did not consider LULUCF for the EU GHG reduction commitments. However, since then, its relevance for climate change mitigation has been acknowledged (EP & C Regulation 841/2013, 2018), and it has finally been included in the current CEP version together with specific accounting rules and monitoring and reporting mechanisms (EP & C Regulation 525/2013, 2013). Having regard to the Treaty on the Functioning of the European Union, and in particular Article 192(1), in order to contribute to the EU's GHG reduction targets along with all the other sectors (EP & C Decision 529/2013, 2013).

However, the CEP just sets general targets whereas the specific GHG emission cuts vary depending on the sector. Economy sectors belonging to the EU *Emissions Trading Scheme* (ETS) (2003/87/EC Directive, 2018)[2] are assigned specific mitigation targets, whilst all the others, including the AFOLU sector, are assigned a mitigation goal as a whole under the *Effort Sharing Mechanism* (EP & C Regulation 842/2013, 2018)[3]. Only a few countries (e.g., Portugal, Ireland) have decided to also assign specific mitigation targets to non-ETS sectors. Nevertheless, it is expected from member states to guarantee that the AFOLU sector will not produce net GHG emissions and that its sinks will improve in the long term.

Apart from the CEPs, there are several other instruments and initiatives at EU-level which pursue the reduction of GHG emissions and thus affect the AFOLU sector. This includes primarily the European Green Deal (EC, 2019) and its legal formulation, the European Climate Law (EC, 2020), the goal of which is to achieve climate neutrality by 2050, and also the Common Agricultural Policy (CAP), established in 1962, which does not target GHG emissions as such, but delivers emissions reductions as co-benefit, mainly in agriculture and, to a lesser extent, in LULUCF.

EU GHG accounting rules

According to the EU Parliament and Council Regulation 841/2018 (EP & C Regulation 841/2013, 2018), member states are to implement updated, robust, and more simplified accountability systems that encompass the AFOLU sector[4] and are based on the earlier ones, which in turn were mainly based on the IPCC 2006 (EP & C Decision 529/2013, 2013; EP & C Regulation 525/2013, 2013). Such systems establish a number of specific accounting guidelines regarding the AFOLU sector specifically which are of course aligned with the IPCC 2006:

- Forest reference emissions levels shall be used instead of the reference year to bypass the different circumstances among the countries.
- Members shall submit to the Commission, national forestry accounting plans (including forest reference levels) to be reviewed, if possible, under the UNFCCC.
- The accounting of removals from managed forests should be done against a forward-looking forest reference emission level based on the extrapolation of forest management practices from a reference period, i.e., a dynamic baseline. A lower level of removals relative to the dynamic baseline should be considered as an emission.

[2] The ETS operates in phases and has undergone several revisions. The latest in 2018 for phase 4.
[3] The ESR translates EU GHG emissions reduction goal of 40% from of all non-ETS sectors by 2030 into specific commitments for each member state.
[4] It refers to the IPCC national GHG inventories guidelines when it comes to wetlands.

2.1.2.2 Forestry and other land uses

Emissions from forestry and other land uses (FOLU) are responsible for 48% of all GHG emissions from the AFOLU sector, predominantly in the form of CO_2. Conversion of forest land is responsible for nearly 60% of all FOLU emissions, followed by emissions from the mineralization of organic matter after the drainage of peat soils on cropland (15%) and grassland (Figure 2.3). CH_4 and N_2O emissions from fires in tropical, temperate, and boreal forests, as well as burning of organic soils correspond to roughly a quarter of total FOLU emissions. In addition to the emissions, forests also act as sinks for atmospheric CO_2 through reforestation and afforestation as well as forest restoration, which partially balance the emissions from the AFOLU sector.

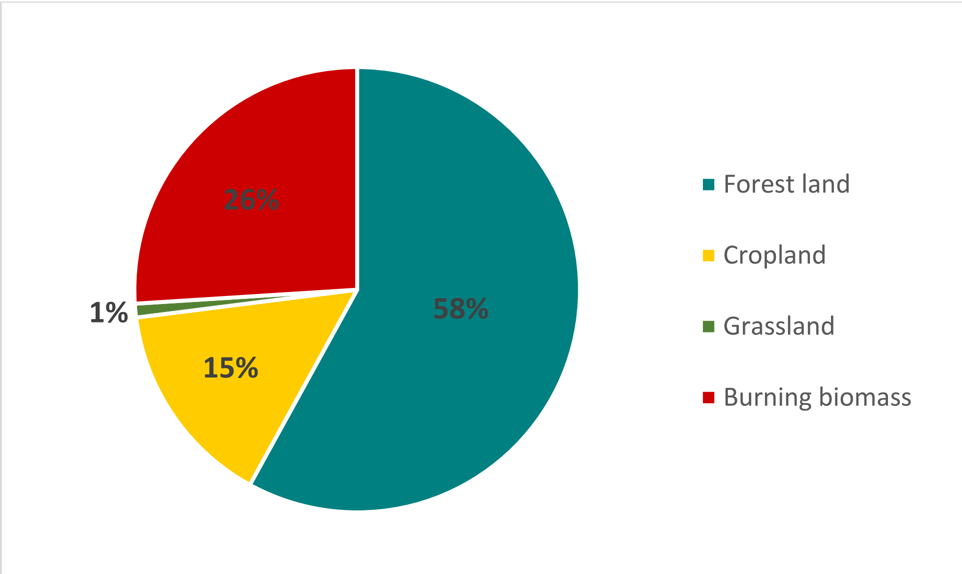

Figure 2.3.Forestry and Other Land Use Emissions by subsector, 2001-2010 (FAO, 2016).

Forest land

This subsection discusses both net forest conversion, leading to CO_2 emissions into the atmosphere, and forests as a sink for CO_2 removals from the atmosphere. While the former refers to changes in forest land area, taking into account both losses and gains (hence 'net'), the latter refers to changes in biomass stocks on existing forest land.

Net forest conversion

Conversion of forest land to other land uses, mainly for agricultural purposes as cropland or grazing land, leads to the emission of CO_2 via the mineralization of carbon in biomass and soil organic matter. In 2014, forest conversion resulted in net emissions of 2,913 Gt CO_2e, corresponding to 58% of all FOLU emissions (FAO, 2016) Almost all (96%) of emissions originate from developing countries, with the Americas taking over 50% of the share, followed by Africa with 26% and Asia with 15% of the total. Oceania and Europe contribute with 5% and 1% of emissions, respectively (FAO, 2016). While there are regional differences in the sign and extent of change, global net forest conversion has been declining at a rate of about 1% per year between 1990 and 2010 (Tubiello *et al.*, 2014).

Reducing deforestation and forest degradation[5] (REDD+) on forest land, afforestation and reforestation of land used for other purposes, and forest restoration represent effective ways of reducing emissions and enhancing removals. Incentivizing the reduction of forest loss requires controlling the drivers of deforestation (e.g., agriculture, mining, infrastructure) and forest degradation (e.g., overharvesting, poor harvesting practices, pests and diseases, wildfires). At the same time it is important to enhance enabling factors,such as the establishment of protected areas, improving law enforcement, establishing forest moratoria, improving forest governance and tenure arrangements, supporting community forest management, and commodity roundtables, among others (Smith *et al.*, 2014, 2019). Reducing deforestation and forest degradation also provides a wide range of co-benefits related to enhancing forest resilience, the provision of ecosystem services, and biodiversity protection (Jia *et al.*, 2019).

While reducing deforestation and forest degradation is about protecting existing forests, afforestation, and reforestation (A/R, sometimes also referred to as forestation) as well as forest restoration increase the biomass stock of trees on deforested and degraded land and can also enhance soil organic matter. A/R occurs where trees are planted either on land that had been forested previously (reforestation) or on land that has historically not been forested (afforestation). While including the planting of native and adapted species, forest restoration, on the other hand, also relies on natural succession processes and a number of instruments to protect forests from drivers of deforestation toenhance their resilience against a range of stressors (Smith *et al.*, 2014, 2019; Pörtner *et al.*, 2021). If well planned, these activities can lead to multiple co-benefits, including improved ecosystem services and greater biodiversity. However, trade-offs can arise where A/R are implemented in ways that do not take sufficiently local social and ecological systems into account, such as by planting monocultures or tree species that are not well adapted to the localities (Smith *et al.*, 2014, 2019; Pörtner *et al.*, 2021).

Forests

Emissions and removals of CO_2 related to forest biomass increase or depletion, including net forest expansion and forest degradation, are inventoried under the 'forests' subsection for bookkeeping reasons although the boundaries to the 'net conversion of forests' subsection are often fluid in practice. CO_2 emissions minus removals from forest land resulted in a net sink of 1,846 Mt CO_2e in 2014, two thirds of which was generated in developed countries (FAO, 2016). The Americas (44%) and Europe (36%) contributed the majority of the net sink, whereas Asia (10%), Africa (5%), and Oceania (5%) contributed less. Although the global net sink strength declined by nearly a third between 1990 and 2000 due to greater losses in developing countries, it has since rebounded at a rate of about 2% per year, mainly in developed countries while stabilizing in developing countries (Tubiello *et al.*, 2014).

Despite some differences, options for mitigation in the 'forests' subsection are strongly aligned with those described in the 'net forest conversion' subsection above and are therefore not replicated here.

[5] For bookkeeping purposes forest degradation is reported under 'forests', but it is addressed here together with reduced deforestation because the 'reduced deforestation and degradation' has become a strong brand. Under the UNFCCC, policies and measures leading to mitigation under this umbrella term are referred to as REDD+, where the + signifies the inclusion of soil organic matter on forest land.

Cropland

Drainage and use of organic soils for agricultural purposes leads to the emission of N_2O and CO_2 as described in subsection 'cultivation of organic soils' above, but only the N_2O emissions are attributed to the agriculture sector whereas the CO_2 emissions arising from the mineralization of carbon in organic soils are addressed under FOLU. CO_2 emissions from agriculturally used peat soils are reported as a constant value and amounted to 724 Mt CO_2e, which is equivalent to 15% of all FOLU emissions (Tubiello *et al.*, 2014; FAO, 2016). Due to variance in peatland composition across the world and differences in the GWP of CO_2 and N_2O, regional attribution is not the same as under 'cultivation of organic soils', such that developing countries contribute two thirds of the GHG emissions (as opposed to a nearly even share for the N_2O emissions). This difference in also reflected in the regional distribution of CO_2 emissions, over half of which originate from Asia, followed by Europe (20%) and the Americas (13%), and Oceania and Africa contributing 7% and 5%, respectively (FAO, 2016).

Options to abate GHG emissions related to agriculturally used peat soils are presented under the 'cultivation of organic soils' subsection above.

Grassland

Similar to the utilization of organic soils for cropland, this subsection details the CO_2 emissions resulting from the use of organic soils for grasslands, adding a constant flow of 26 Mt CO_2e per year and thus contributing with less than 1% to the total FOLU emissions (FAO, 2016). Asia contributes the most with 42% of subsector emissions, followed by Africa, the Americas, and Europe with 21%, 20%, and 17%, respectively, while Oceania's share is negligible.

Options to abate GHG emissions related to agriculturally used peat soils are presented under the 'cultivation of organic soils' subsection above.

Burning biomass

This subsection captures CH_4 and N_2O emissions from the burning of biomass in forests (CO_2 emissions are captured under 'forest land') and CO_2, CH_4, and N_2O emissions from burning peat soils not used for agricultural purposes. In 2014, emissions amounted to 1,303 Mt CO_2e, that is roughly a quarter of all emissions related to FOLU of which ca. two thirds originated from developing countries (FAO, 2016). Disaggregating by source, 59% of emissions originated from organic soils, whereas 27% arose from humid tropical forests and 14% from other forests (Tubiello *et al.*, 2014). From a regional perspective, Africa's contribution to the total was the largest with 40%, followed by the Americas (26%), Europe (19%), and Asia (13%), whereas Oceania's share was small with 2% (FAO, 2016).

Options to abate emissions from biomass burning correspond primarily to measures presented under 'forest land', as clearing of the forests is often done using fire.

Box 2.2.The Netherlands' main mitigation strategies in the AFOLU sector
Although the Netherlands has seen a clear reduction in GHG emissions over the past decades (27.3% since 1990), in 2018 GHG emissions from agriculture were still responsible for nearly 10% of all national GHG emissions, with CH_4 from enteric fermentation representing the highest share of all emissions from the sector (45.3% in 2018) (Mandl *et al.*, 2020). In addition, LULUCF GHG emissions were 2.5% of total GHG emissions in 2018, despite having decreased by 24% compared to 1990 levels, mostly due to reductions in grasslands GHG emissions (RIVM, 2020). The Netherlands has set a national goal of reducing GHG emissions in 49% in 2030 and by 95% by 2050 compared with 1990 levels. The main instruments to achieve this goal are the Climate Act (2019), which requires the government to develop a Climate Plan, where general mitigation measures will be drawn up, and the National Climate Agreement (2019), which contains the sector specific measures agreed with sectoral stakeholders to achieve the national targets. The main political instrument to address AFOLU GHG emissions at national level is the 2008 *Clean and Efficient Agro-Sectors Covenant*. It sets CO_2 and non-CO_2 (mainly N_2O and CH_4) GHG emissions reduction targets with focus on the livestock, dairy, and horticulture sectors, including: • Livestock management (e.g. lifespan extension); • Improved soil management (e.g. precision fertilizing); • Reduced deforestation; • Intensification of the use of greenhouses as energy sources in the horticulture. In addition, apart from the national policies, some European policies have significantly influenced the evolution of the Netherland's AFOLU GHG emissions, although not always towards lower emissions. For instance, the removal of the EU milk quota opened the way to breed more dairy cattle increasing indirect GHG emissions (RIVM, 2020) compared with 2015 emissions. To counteract this, an act regulating animal numbers, manure production, and fertilizer use has been passed.

2.2 Mitigation options in the AFOLU sector

Tables 2.2 and 2.3 provide overview information on a selection of key mitigation practices in the AFOLU sector. Table 2.2 is extracted from the IPCC Special Report on Climate Change and Land (Smith *et al.*, 2019) as well as the first IPBES-IPCC synthesis report focusing on the interactions of climate change and biodiversity (Pörtner *et al.*, 2021). The table presents an overview of mitigation options ordered by their minimum global technical mitigation potentials as well as their contributions to adaptation and biodiversity. Options partially overlap and their mitigation benefits are therefore not additive. The tabulated mitigation potentials are derived from the IPCC Special Report on Climate Change and Land (Smith *et al.*, 2019), the IPCC Special Report on 1.5°C (Hoegh-Guldberg *et al.*, 2018), and a recent paper on the land sector's contribution to a 1.5°C world (Roe *et al.*, 2019) and thus present the best available internationally recognized summary information on the topic. However, while large mitigation potentials are important due to the possibility of measures contributing to reducing emissions or enhancing sinks at the global scale, at local to national scales mitigation potentials mainly depend on context-specific land-use options and also need to be assessed in view of their effects on a range of other demands to land, such as for food, water, or energy, etc. Moreover, if done without due diligence, mitigation measures can impact the natural resource base with trade-offs related to ecosystem services and biodiversity and thus affect the resilience of social-ecological systems against current and future climate change. On the other hand, if well planned and executed, GHG mitigation can lead to multiple co-benefits for ecosystem integrity as well as jobs and livelihoods (Smith *et al.*, 2019). Table 2.3 shows the same mitigation options with additional information regarding their key features as well as information on contexts and potential caveats for implementation that is taken verbatim from the SRCCL (Smith *et al.*, 2019). In addition, Table 2.3 provides information how to report mitigation outcomes using the IPCC national GHG inventories.

The mitigation options presented focus exclusively on supply-side measures related to the AFOLU sector. Although their mitigation potentials are considered high to very high (Smith *et al.*, 2014; Mbow *et al.*, 2019), measures connected to the wider food system and the bioeconomy, such as dietary change, reducing post-harvest losses and food waste, supply-chain management, improved food processing, and material substitution of fossil fuel-based products (e.g. textiles, construction materials) are not considered further as they are not reported under AFOLU in the national GHG inventories. They should nevertheless be taken into account when raising ambitions for climate action by planning for more integrated solutions with broad societal, environmental, and health-related co-benefits (Smith *et al.*, 2014, 2019; Pörtner *et al.*, 2021).

Table 2.2. Effects of selected (example) global climate mitigation practices in the AFOLU sector, ordered by minimum mitigation potentials, next to their effects on adaptation1).

Practice	Mitigation potential (Gt CO_2e yr^{-1})	Adaptation potential [2)] (million people)	Biodiversity impact
Mitigation options in agriculture			
Increased food productivity	> 13	> 163	High [3)] or low [4)] positive
Improved cropland management	1.4-2.1	> 25	Medium positive
Improved grazing land management	1.4-1.8	1-25	Medium positive
Increased soil organic carbon content	0.4-8.6	Up to 3,200	Medium positive
Improved livestock management	0.2-2.4	1-25	Medium positive
Agroforestry	0.1-5.7	2,300	High positive
Mitigation options on forest land			
Reforestation and forest restoration	1.5-10.1	> 25	High positive
Afforestation	See reforestation	Unclear	Negative or low positive [5)]
Reduced deforestation and degradation	0.4-5.8	1-25	High positive
Improved forest management	0.4-2.1	> 25	High positive
Mitigation options in all/other land uses			
Restoration and reduced conversion of peatlands	0.6-2	No global estimates	High positive
Fire management	0.48-8.1	> 5.8affected by wildfire [6)]	Low positive
Restoration and reduced conversion of coastal wetlands	0.3-3.1	Up to 93-310	High positive
Biochar addition to soil	0.03-6.6	Up to 3,200 [7)]	Low positive [8)]
Reduced grassland conversion to cropland	0.03-0.7	No global estimates	High positive [9)]

1) Mitigation options often overlap, so are not additive (modified from Hoegh-Guldberg et al., 2018; Roe et al., 2019; Smith et al., 2020). Biodiversity impact based on McElwee et al., (2020) and Girardin et al., (2021). See these sources for further references, uncertainties and confidence levels.
2) Estimated number of people more resilient to climate change from intervention
3) If achieved through sustainable intensification; 4) If achieved through increased agricultural inputs; 5) If small scale; 6) Max. 0.5 million deaths per year by smoke; 7) But potential negative (unquantified) impacts if arable land used for feedstock production; 8) If biochar is sourced from forest ecosystems, application can be beneficial to soils locally; 9) If conversion takes place in (semi-)natural grassland.

Table 2.3. Effects of selected (example) global climate mitigation practices in the AFOLU sector, ordered by minimum mitigation potentials, next to their effects on adaptation and biodiversity (Smith *et al.*, 2019).

Integrated response option	Description	Context and caveats	Links to source and sink categories in NGHGI
Mitigation options in agriculture			
Increased food productivity	Increased food productivity arises when the output of food commodities increases per unit of input, e.g., per unit of land or water. It can be realised through many other interventions such as improved cropland, grazing land and livestock management.	Many interventions to increase food production, particularly those predicated on very large inputs of agrochemicals, have a wide range of negative externalities leading to the proposal of sustainable intensification as a mechanism to deliver future increases in productivity that avoid these adverse outcomes. Intensification through additional input of nitrogen fertiliser, for example, would result in negative impacts on climate, soil, water and air pollution. Similarly, if implemented in a way that over-exploits the land, significant negative impacts would occur, but if achieved through sustainable intensification, and used to spare land, it could reduce the pressure on land.	• Changes in SOM of mineral and organic soils • Changes in crop residues • Changes in organic and synthetic fertilizers • Possible changes in manure management and enteric fermentation • Possible changes in CH_4 and N_2O from rice cultivation • Possible changes in land use
Improved cropland management	Improved cropland management is a collection of practices consisting of a) management of the crop: including high input carbon practices, for example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology, b) nutrient management: including optimised fertiliser application rate, fertiliser type (organic manures, compost and mineral), timing, precision application, nitrification inhibitors, c) reduced tillage intensity and residue retention, d) improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions, e) improved rice management: including water management such as mid-season drainage and improved fertilisation and residue management in paddy rice systems, and f) biochar application.	Improved cropland management can reduce GHG emissions and create soil carbon sinks, though if poorly implemented, it could increase nitrous oxide and methane emissions from nitrogen fertilisers, crop residues and organic amendments. It can improve resilience of food crop production systems to climate change and can be used to tackle desertification and land degradation by improving sustainable land management. It can also contribute to food security by closing crop yield gaps to increase food productivity.	• Changes in SOM of mineral and organic soils • Changes in crop residues • Changes in organic and synthetic fertilizers • Possible changes in CH_4 and N_2O from rice cultivation • Possible changes in biomass through set-side and land-use change
Improved grazing land management	Improved grazing land management is a collection of practices consisting of a) management of vegetation: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management, b) animal management: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification, and c) fire management: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning. (see also fire management as a separate response option)	Improved grazing land management can increase soil carbon sinks, reduce GHG emissions, improve the resilience of grazing lands to future climate change, help reduce desertification and land degradation by optimising stocking density and reducing overgrazing, and can enhance food security through improved productivity.	• Changes in SOM of mineral and organic soils • Changes in organic and synthetic fertilizers • Changes in manure remaining on grazing land • Possible changes in biomass through set-side and land-use change
Increased soil organic carbon content	Practices that increase soil organic matter content include a) land-use change to an ecosystem with higher equilibrium soil carbon levels (e.g., from cropland to forest), b) management of the vegetation: including high input carbon practices, for example, improved varieties, rotations and cover crops, perennial cropping systems, biotechnology to increase	Increasing soil carbon stocks removes CO_2 from the atmosphere and increases the water-holding capacity of the soil, thereby conferring resilience to climate change and enhancing adaptation capacity. It is a key strategy for addressing both desertification and land degradation. There is some evidence that crop yields and yield stability increase by increased organic matter content, though	• Changes in SOM of mineral and organic soils through application of manure, crop residues, biochar, etc.

	inputs and recalcitrance of below ground carbon, c) nutrient management and organic material input to increase carbon returns to the soil, including: optimised fertiliser and organic material application rate, type, timing and precision application, d) reduced tillage intensity and residue retention, and e) improved water management: including irrigation in arid/semi-arid conditions.	some studies show equivocal impacts. Some practices to increase soil organic matter stocks vary in their efficacy. For example, the impact of no-till farming and conservation agriculture on soil carbon stocks is often positive, but can be neutral or even negative, depending on the amount of crop residues returned to the soil. If soil organic carbon stocks were increased by increasing fertiliser inputs to increase productivity, emissions of nitrous oxide from fertiliser use could offset any climate benefits arising from carbon sinks. Similarly, if any yield penalty is incurred from practices aimed at increasing soil organic carbon stocks (e.g., through extensification), emissions could be increased through indirect land-use change, and there could also be adverse side effects on food security.	• Changes in SOM of mineral and organic soils through tillage and water management • Changes in biomass through set-side and land-use change
Improved livestock management	Improved livestock management is a collection of practices consisting of a) improved feed and dietary additives (e.g., bioactive compounds, fats), used to increase productivity and reduce emissions from enteric fermentation; b) breeding (e.g., breeds with higher productivity or reduced emissions from enteric fermentation), c) herd management, including decreasing neo-natal mortality, improving sanitary conditions, animal health and herd renewal, and diversifying animal species, d) emerging technologies (of which some are not legally authorised in several countries) such as propionate enhancers, nitrate and sulphate supplements, archaea inhibitors and archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics, ionophores/antibiotics; and e) improved manure management, including 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.	Improved livestock management can reduce GHG emissions, particularly from enteric methane and manure management. It can improve the resilience of livestock production systems to climate change by breeding better adapted livestock. It can help with desertification and land degradation, e.g., through use of more efficient and adapted breeds to allow reduced stocking densities. Improved livestock sector productivity can also increase food production.	• Changes in CH_4 emissions from enteric fermentation through feeding, breeding, animal health, herd management, etc. • Changes in CH_4 and N_2O emissions from manure management • Potentially changes in biomass and SOM through set-side and land-use change
Agroforestry	Agroforestry involves the deliberate planting of trees in croplands and silvo-pastoral systems.	Agroforestry sequesters carbon in vegetation and soils. The use of leguminous trees can enhance biological nitrogen fixation and resilience to climate change. Soil improvement and the provision of perennial vegetation can help to address desertification and land degradation. Agroforestry can increase agricultural productivity, with benefits for food security. Additionally, agroforestry can enable payments to farmers for ecosystem services and reduce vulnerability to climate shocks.	• Changes in biomass (above and below ground) due to integration of trees into cropland and pastures • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Mitigation options on forest land			
Reforestation and forest restoration	Reforestation is the conversion to forest of land that has previously contained forests but that has been converted to some other use. Forest restoration refers to practices aimed at regaining ecological integrity in a deforested or degraded forest landscape. As such, it could fall under reforestation if it were re-establishing trees where they have been lost, or under forest management if it were restoring forests where not all trees have been lost. For practical reasons, here forest restoration is treated together with reforestation.	Reforestation is similar to afforestation with respect to the co-benefits and adverse side effects among climate change mitigation, adaptation, desertification, land degradation and food security (see row on Afforestation below). Forest restoration can increase terrestrial carbon stocks in deforested or degraded forest landscapes and can offer many co-benefits in terms of increased resilience of forests to climate change, enhanced connectivity between forest areas and conservation of biodiversity hotspots. Forest restoration may threaten livelihoods and local access to land if subsistence agriculture is targeted.	• Changes in biomass (above and below ground) due to reforestation and forest restoration • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils

Afforestation	Afforestation is the conversion to forest of land that historically have not contained forests. (see also 'reforestation')	Afforestation increases terrestrial carbon stocks but can also change the physical properties of land surfaces, such as surface albedo and evapotranspiration with implications for local and global climate. In the tropics, enhanced evapotranspiration cools surface temperatures, reinforcing the climate benefits of CO_2 sequestration in trees. At high latitudes and in areas affected by seasonal snow cover, the decrease in surface albedo after afforestation becomes dominant and causes an annual average warming that counteracts carbon benefits. Net biophysical effects on regional climate from afforestation is seasonal and can reduce the frequency of climate extremes, such as heat waves, improving adaptation to climate change and reducing the vulnerability of people and ecosystems. Afforestation helps to address land degradation and desertification, as forests tend to maintain water quality by reducing runoff, trapping sediments and nutrients, and improving groundwater recharge. However, food security could be hampered since an increase in global forest area can increase food prices through land competition. Other adverse side effects occur when afforestation is based on non-native species, especially with the risks related to the spread of exotic fast-growing tree species. For example, exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability, particularly in dry regions.	• Changes in biomass (above and below ground) due to afforestation • Changes in biomass through land-use change • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Reduced deforestation and degradation	Reduced deforestation and forest degradation includes conservation of existing carbon pools in forest vegetation and soil 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), also through establishing protected areas, improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification.	Reducing deforestation and forest degradation is a major strategy to reduce global GHG emissions. The combination of reduced GHG emissions and biophysical effects results in a large climate mitigation effect, with benefits also at local level. Reduced deforestation preserves biodiversity and ecosystem services more efficiently and at lower costs than afforestation/reforestation. Efforts to reduce deforestation and forest degradation may have potential adverse side effects, for example, reducing availability of land for farming, restricting the rights and access of local people to forest resources (e.g., firewood), or increasing the dependence of local people to insecure external funding.	• Changes in biomass (above and below ground) due to avoided deforestation and forest degradation • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Improved forest management	Forest management refers to management interventions in forests for the purpose of climate change mitigation. It includes a wide variety of practices affecting the growth of trees and the biomass removed, including improved regeneration (natural or artificial) and a better schedule, intensity and execution of operations (thinning, selective logging, final cut, reduced impact logging, etc.). 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.	Sustainable forest management can enhance the carbon stock in biomass, dead organic matter, and soil – while providing wood-based products to reduce emissions in other sectors through material and energy substitution. A trade-off exists between different management strategies: higher harvest decreases the carbon in the forest biomass in the short term but increases the carbon in wood products and the potential for substitution effects. Sustainable forest management, also through close-to-nature silvicultural techniques, can potentially offer many co-benefits in terms of climate change mitigation, adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection, coastal area protection and water and flood regulation. Forest management strategies aimed at increasing the biomass stock levels may have adverse side effects, such as decreasing the stand-level structural complexity, biodiversity and resilience to natural disasters. Forest management also affects albedo and evapotranspiration.	• Changes in biomass (above and below ground) due to forest management and restoration • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils • Potentially changes in biomass and SOM through set-side and land-use change

Mitigation options in all/other land uses			
Restoration and reduced conversion of peatlands	Peatland restoration involves restoring degraded/ damaged peatlands, which both increases carbon sinks, but also avoids ongoing CO_2 emissions from degraded peatlands. So, as well as protecting biodiversity, it both prevents future emissions and creates a sink.	Avoided peat impacts and peatland restoration can provide significant mitigation, though restoration can lead to an increase in methane emissions, particularly in nutrient rich fens. There may also be benefits for climate adaptation by regulating water flow and preventing downstream flooding. Considering that large areas of global peatlands are degraded, peatland restoration is a key tool in addressing land degradation. Since large areas of tropical peatlands and some northern peatlands have been drained and cleared for food production, their restoration could displace food production and damage local food supply, potentially leading to adverse impacts on food security locally, though the global impact would be limited due to the relatively small areas affected.	• Changes in SOM of organic soils due to land-use change • Changes in biomass through land-use change • Possible changes in CH_4 and N_2O due to peatland restoration
Fire management	Fire management is a land management option aimed at safeguarding life, property and resources through the prevention, detection, control, restriction and suppression of fire in forest and other vegetation. It includes the improved use of fire for sustainable forestry management, including wildfire prevention and prescribed burning. Prescribed burning is used to reduce the risk of large, uncontrollable fires in forest areas, and controlled burning is among the most effective and economic methods of reducing fire danger and stimulating natural reforestation under the forest canopy and after clear felling.	The frequency and severity of large wildfires have increased around the globe in recent decades, which has impacted on forest carbon budgets. Fire can cause various GHG emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and others such as carbon monoxide (CO), volatile organic carbon, and smoke aerosols. Fire management can reduce GHG emissions and can reduce haze pollution, which has significant health and economic impacts. Fire management helps to prevent soil erosion and land degradation and is used in rangelands to conserve biodiversity and to enhance forage quality.	• Changes in biomass through fire management • Changes in the emission of CH_4 and N_2O due to reduced fires on cropland and grasslands • Possible changes in crop residues
Restoration and reduced conversion of coastal wetlands	Coastal wetland restoration involves restoring degraded/ damaged coastal wetlands, including mangroves, salt marshes and seagrass ecosystems.	Coastal wetland restoration and avoided coastal wetland impacts have the capacity to increase carbon sinks and can provide benefits by regulating water flow and preventing downstream flooding. Coastal wetlands provide a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments. Since large areas of global coastal wetlands are degraded, restoration could provide benefits land degradation. Since some areas of coastal wetlands are used for food production, restoration could displace food production and damage local food supply, though some forms (e.g., mangrove restoration) can improve local fisheries.	• Changes in SOM of soils due to land-use change • Changes in biomass through land-use change
Biochar addition to soil	The use of biochar, a solid product of the pyrolysis process, as a soil amendment increases the water-holding capacity of soil. It may therefore provide better access to water and nutrients for crops and other vegetation types (so can form part of cropland, grazing land and forest management).	The use of biochar increases carbon stocks in the soil. It can enhance yields in the tropics (but less so in temperate regions), thereby benefitting both adaptation and food security. Since it can improve soil water-holding capacity and nutrient-use efficiency, and can ameliorate heavy metal pollution and other impacts, it can benefit desertification and land degradation. The positive impacts could be tempered by additional pressure on land if large quantities of biomass are required as feedstock for biochar production.	• Changes in SOM of mineral soils • Possible changes in N_2O emissions from fertilizers
Reduced grassland conversion to cropland	Grasslands can be converted to croplands by ploughing of grassland and seeding with crops. Since croplands have a lower soil carbon content than grasslands and are also more prone to erosion than grasslands, reducing conversion of grassland to croplands will prevent soil carbon losses by oxidation and soil loss through erosion. These processes can be reduced if the rate of grassland conversion to cropland is reduced.	Stabilising soils by retaining grass cover also improves resilience, benefitting adaptation, desertification and land degradation. Since conversion of grassland to cropland usually occurs to remedy food security challenges, food security could be adversely affected, since more land is required to produce human food from livestock products on grassland than from crops on cropland.	• Changes in SOM of mineral and organic soils through land-use change • Changes in biomass through land-use change

2.2.1 Mitigation options in agriculture

Mitigation options related to agriculture are presented in Table 2.2 and include increased food productivity, improved cropland management, improved grazing land management, increased soil organic carbon content, improved livestock management, and agroforestry. Mitigation in agriculture is achieved through a wide range of measures that lead to both reducing GHG emissions, primarily N_2O and CH_4 from crop and livestock systems, and enhancing the CO_2 sink through improved soil management and additional biomass.

2.2.1.1 Increased food productivity

Increased food productivity encloses a range of interventions such as improved cropland, grazing land, and livestock management that lead to higher production per unit input (e.g., fertilizer, water), several of which are described in greater detail in the following subsections and in Table 2.3. Productivity increases are not restricted to food and can equally be described for feed, fibres, forest products, etc. and ultimately lead to lower GHG emissions per unit produce from the land (sustainable intensification). This gain in productivity may translate into land sparing if the same demand can be produced on a smaller amount of land and could therefore be a way to reduce deforestation and forest degradation or limit the conversion of other natural land uses into cropland or grazing land. Considering that sustainable intensification can be achieved through measures related to soil, water, crop, livestock, and/or manure management, changes in the national GHG inventory (NGHGI) could arise in most agricultural source categories as well as in FOLU categories.

2.2.1.2 Improved cropland management

Improved cropland management encompasses a number of practices consisting of crop management, nutrient management, tillage, and water management, including for rice, and biochar application. Examples of possible measures that can all contribute to GHG mitigation, food security, system resilience to climate change, and reduction of land degradation if implemented with care and consideration of environmental and social constraints are provided in Table 2.3. However, if poorly implemented, measures could enhance emissions of N_2O and CH_4 from nitrogen fertilizers, crop residues, and organic amendments. In the NGHGI, improved cropland management can be reflected via changes in SOM of mineral and organic soils, the amount of crop residues, fertilizers applied, management of rice paddies, and, potentially, changes in biomass through land-use change if the measures lead to sustainable intensification and land sparing.

2.2.1.3 Improved grazing land management

Improved grazing land management includes a range of different practices, consisting of vegetation management, animal management, and fire management. Examples of possible measures include improved grass varieties and better nutrient management for higher productivity; appropriate livestock densities and feed diversification to reduce overgrazing; and use of fire as a sustainable management tool (see Table 2.3 for a list of specific measures). These practices can contribute to mitigation through reduced GHG emissions and enhanced soil carbon sinks, improve grazing land resilience to climate impacts through more adapted species, reduce land degradation, and improve food security through greater productivity of the land. Mitigation through improved grazing land management can be reflected in GHG inventories via changes in SOM contents, changes in emissions from mineral and organic fertilizers, and possible changes in biomass due to land sparing after productivity gains.

2.2.1.4 Increased organic carbon content

Practices resulting in an increase in soil carbon contents ultimately rely on increasing the amount of biomass from plant residues and organic materials (e.g., biochar, compost) entering the soil, as well as by reducing mineralization processes (e.g., from organic soils or reduced tillage). This can be achieved through changes in land use toward ecosystems with higher equilibrium carbon stocks (e.g., from cropland to rangeland or forest); vegetation management (e.g., cover crops, perennial cropping); nutrient management to enhance the return of biomass to the soil; tillage management (e.g., no till); and improved water management to boost production (see Table 2.3 for a list of specific measures). Besides sequestering atmospheric carbon in the soil, higher SOM levels also improve soil health through greater water holding capacity, porosity, fertility, and soil biology (micro-, meso-, and macro-fauna). While there are few downsides from increased SOM levels, care must be taken to avoid indirect land-use change if higher soil carbon contents go hand in hand with lower production levels facilitating leakage. In the NGHGI an increase in soil carbon can be reported through changes in SOM contents as well as changes in biomass as the consequence of land-use change.

2.2.1.5 Improved livestock management

Improved livestock management is an umbrella term for a number of practices consisting of advancements in feed and additives to improve animal health, breeding, herd management, and manure management, next to emerging technologies to, for example, reduce methanogenesis in the rumen (see Table 2.3 for a more detailed list of measures to improve livestock management). These measures can have strong effects on GHG emissions, primarily via reductions in emissions from enteric fermentation and manure management. They can also improve livestock health and resilience to climate and other environmental hazards while potentially enhancing food production (Smith *et al.*, 2019). In the context of the NGHGI, mitigation via improved livestock management is primarily reported through changes in emissions from enteric fermentation and manure management. Where higher livestock productivity results in reduced pressure on land, there is also a possibility of biomass and SOM increase related to land-use change contributing to mitigation.

Box 2.3.Indonesia's main mitigation strategies in the AFOLU sector
Indonesia is an example of a developing country with high GHG emissions, a majority of which arise from LULUCF. Approximately 60% of all national GHG emissions in 2005 were due to deforestation and emissions from peat soils (Thamrin, 2011). In contrast, the agriculture sector was responsible for only 5% of the total national GHG emissions, most of which from rice cultivation, enteric fermentation, and fertilizers applied to agricultural soils (Thamrin, 2011). Indonesia's 2016 NDC includes an unconditional 26% GHG reduction target by 2030 relative to the BAU. This should occur mainly in the AFOLU and energy sectors andmight become 41% if the required international support is received (Henderson *et al.*, 2020). To do so, a first *National Action Plan* (NAP), covering 2010-2020, was developed. This plan was intended to serve as a framework and guidance for the development of the required initiatives and actions. In addition to this, almost all regional governments also elaborated their own plans in line with the NAP. The NAP includes 23

measures for the LULUCF sector and 7 for the agriculture sector, with specific targets to be achieved by 2020, including:

- Use of organic fertilizers and bio-pesticides;
- Increase productivity of perennial crops;
- No burning management;
- Use of cattle urine/manure for biogas;
- Forest rehabilitation.

Most of the mitigation policies specific to the AFOLU developed under the NAP address the forestry sector, given Indonesia’s extensive forest area (63% of the total national surface) and the relevance of the subsequent GHG emissions. Forests and peatland contain the largest carbon stocks, however they are at risk due to peat mineralization after drainage, deforestation, and forest degradation, which are some of the threats the Indonesian authorities try to address through a number of policies:

- Forest moratorium to prevent the conversion of primary forests and peatlands into plantations, thereby curbing emissions. It has been identified as one of the policies with the highest mitigation potential worldwide. However, it only affects new licenses, thus, already given licenses covering forest area remain out of its reach. Besides, since the policy will only be effective if it is implemented at local level, the lack of mandate, resources, and guidelines at that level is delaying its full implementation.
- Peat ecosystems protection and restauration mainly through rewetting and revegetation.
- Forest and landscape rehabilitation (tree planting, reforestation, and land reclamation activities).
- Forest and wildfire control (through early warning systems, capacity building, stronger law enforcement, and international cooperation for hotspots identification).

In addition, some international initiatives are also contributing to curb of GHG emissions and the achievement of NDC targets in Indonesia such as the REDD+ Programme for the reduction of GHG emissions in AFOLU sector.

2.2.1.6 Agroforestry

Agroforestry is the deliberate association of trees within croplands and grazing lands, which can take place in a wide range of ways and has been described for both high and low input agricultural systems (Mbow *et al.*, 2019). By combining crops, livestock, and trees, agroforestry systems produce a greater diversity of products and enhance productivity through higher land equivalent ratios[6] (Graves *et al.*, 2010; van Noordwijk *et al.*, 2018; Khasanah *et al.*, 2020). Due to the presence of trees in cropping and pastoral settings, agroforestry systems contribute to mitigation by sequestering carbon in biomass and soils. Agroforestry typically leads to a range of agroecological benefits, such as improved ecosystem services and biodiversity through system diversification. In addition, next to mitigation, agroforestry enhances resilience against climate shocks, contributes to reducing degradation, and improves food security (Mbow *et al.*, 2019; Smith *et al.*, 2019). In the NGHGI, mitigation through agroforestry can be reflected through changes in biomass and possibly changes in SOM. If the tree component produces wood, there can also be changes in harvested wood products (HWP). Where higher productivity leads to land sparing, changes in biomass and SOM can also accrue due to land-use change.

[6] The land equivalent ratio is a concept in agriculture that describes the relative land area required under monoculture to produce the same yield as under polyculture (Mead *et al.*, 1980).

2.2.2 Mitigation options on forest land

Mitigation options related to forest land presented here are taken from Smith et al. (2019) and include reforestation and forest restoration, afforestation, reduced deforestation and degradation, and improved forest management (see Table 2.3 for more details). Mitigation is achieved primarily by enhancing the CO_2 sink through additional tree biomass (both above and below ground) and greater soil carbon contents compared to other land uses or avoiding deforestation and forest degradation. Where trees are harvested, there can also be mitigation via HWP.

2.2.2.1 Reforestation and forest restoration

Reforestation is the conversion of land to forest that has previously contained forests but that has been converted to some other use (Smith et al., 2019). Forest restoration contains practices that contribute to regaining ecological integrity of previously deforested land or degraded forests. In Smith *et al.* (2019) forest restoration is combined with reforestation for practical reasons although it could be listed under forest management where forests are degraded but have not lost all trees. Reforestation and forest restoration contribute to climate change mitigation through increased terrestrial carbon stocks in biomass and, where forests substitute land uses with lower SOM, in soils. If implemented well, reforestation can enhance resilience to climate impacts and reduce landscape degradation by improving ecosystem services such as buffering water flow and improving water quality. Where reforestation and forest restoration are carried out with adapted and endemic species and increase the connectivity between biodiversity hotspots (e.g., natural forests), there can also be great benefits for biodiversity. However, reforestation can potentially displace subsistence agriculture and thereby negatively affect livelihoods and food security and, hence, needs to be considered in the context of access to land and land tenure (Smith *et al.*, 2019). More information on the effects of reforestation and forest restoration, including on the regional climate, can be found in Table 2.3. In the NGHGI, mitigation via reforestation and forest restoration is reported as changes in biomass and SOM as well as, potentially, via changes in HWP.

2.2.2.2 Afforestation

Afforestation is the conversion to forest of land that historically has not contained forests (Smith *et al.*, 2019). If done well, afforestation can have similar benefits as reforestation (see above and in Table 2.3). Without careful implementation afforestation can lead to similar trade-offs as reforestation, which may be exacerbated where trees are planted on land that is not suited for forests, particularly in dry regions where the trees can diminish water availability and change the composition of local fauna and flora (Smith *et al.*, 2014, 2019; Pörtner *et al.*, 2021). In the NGHGI, mitigation through afforestation is reported as changes in biomass and SOM as well as, potentially, via changes in HWP.

2.2.2.3 Reduced deforestation and degradation

Reduced deforestation and forest degradation (REDD+) includes a range of measures that lead to the conservation of existing carbon pools in forests, primarily by controlling the drivers of deforestation, in particular agriculture, mining, and infrastructure development, and forest degradation, including overharvesting and poor harvesting practices, overgrazing, fuelwood collection, pests, and wildfires (Smith *et al.*, 2019). However, often it is not possible to control the direct drivers without addressing the underlying drivers, such as demand for commodities, development strategies, poor governance and law enforcement, poverty, or access and tenure rights (Geist *et al.*, 2002; Kissinger *et al.*, 2012; Curtis *et al.*, 2018; Seymour *et al.*, 2019). Where implemented successfully, REDD+ can be a powerful strategy to reduce GHG emissions with large positive effects on climate resilience, ecosystem services, and biodiversity preservation (Smith *et al.*, 2019). Considering that REDD+ avoids the emission of GHGs, in the NGHGI no changes in biomass and SOM would occur if deforestation and forest degradation have been fully averted. Therefore, mitigation would be achieved by comparing the existing terrestrial carbon stock with a scenario in which the drivers have not been stopped.

2.2.2.4 Improved forest management

Forest management refers to interventions in forests with the main purpose of enhancing biomass production and includes practices such as natural and artificial regeneration and better scheduling, intensity, and execution of forest management activities (Smith *et al.*, 2019). Table 2.3 provides a few examples. Sustainable forest management supports the stewardship and use of forests in ways and at rates that are consistent with long-term sustainability criteria to maintain their biodiversity, productivity, and regeneration capacity in order to provide relevant ecological, economic, and social functions (Smith *et al.*, 2019). Where forest restoration deals with degraded forests it would also fall under the umbrella of improved forest management. Besides maintaining and enhancing the carbon stock, improved forest management can potentially offer a range of co-benefits, including adaptation, biodiversity conservation, microclimatic regulation, erosion control, and flood protection, among others (Smith *et al.*, 2019). Similar to the other mitigation options on forest lands, improved forest management can be reported within the NGHGI as changes in biomass and SOM, as well as changes in HWP. Where higher forest productivity reduces pressures on the expansion of forests to meet demands for forest products, for example through afforestation or reforestation, there may also be changes in biomass and SOM through avoided land-use change elsewhere.

Box 2.4.Ireland's main mitigation strategies in the AFOLU sector

In2018, agriculture accounted for 32.7% of national GHG emissions (much higher than in the rest of the EU (ca.10%) and totalling 4.5% of all EU agriculture GHG emissions (Henderson *et al.*, 2020). However, it is expected that the emissions share of the AFOLU sector will increase due to the decarbonization of other sectors. Given the relevance of its agriculture emissions, Ireland enjoys some flexibility in the sectoral emissions shares allowed by the EU.

The *Climate Action Plan* (CAP), launched in 2019, is Ireland's main AFOLU GHG emissions-related policy instrument, setting the pathway to decarbonization until 2030. AFOLU specific goals include:

- 16.5-18.5 Mt CO_2e (8-9%) reduction in agricultural GHG emissions by 2030 compared to 2017 levels.
- 26.8 Mt CO_2e (13%) reduction in LULUCF GHG emissions, mainly through afforestation and reduction of the management intensity of peatland.
- Raising transparency about the GHG emissions reductions due to the CAP and other policies, how these are reflected in GHG inventories, and how to improve MRV of abatement options.

To curb emissions and achieve those goals, the CAP foresees the implementation of a number of measures and actions in agriculture that fall under four categories:

- Enhance soil fertility and nutrient efficiency.
- Promote the use of protected N products.

- Control crude protein content of animal feed.
- Develop enhanced dairy and breeding programmes.

For LULUCF, the CAP proposes reviewing the national forestry programme, the introduction of goals such as the improvement of soil and peatland management and increasing bioenergy feedstocks to produce biogas and biomethane. Specific actions proposed to achieve the CAP goals relative to LULUCF include:

- Planting of new forests under the 1990 Afforestation Scheme, which encourages farmers to convert land from agriculture production to forestry (for timber and biomass for bioenergy) to reach 18% of forest-covered land by 2050. Most of the expansion will be implemented by farmers.
- Improve forest management.
- Lower management intensity of grasslands, arable land, and wetlands.
- National Peatland Strategy.
- Research programmes.

In addition, the EU Common Agriculture Policies has affected Ireland's AFOLU sector mainly through its Rural Development Programme, as some of Ireland's budget is dedicated to actions leading to GHG emissions reductions as co-benefits:

- Targeted Agricultural Modernisation Schemes, TAMS II.
- Green, Low-Carbon, Agri-Environment Scheme (GLAS) offers payments to farmers to implement climate-change conscious agricultural production methods (nutrients management, low input pasture, minimum tillage, and low manure spreading techniques).
- Beef Data and Genomic Programme: Improving genetical traits of the national beef herd.
- Organic Farming Scheme.

2.2.3 Mitigation options in all/other land uses

Options to reduce GHG emissions or enhance carbon sinks in other land uses presented here are taken from Smith *et al.* (2019) and include restoration and reduced conversion of peatlands, fire management, restoration and reduced conversion of coastal wetlands, biochar addition to soil, and reduced grassland conversion to cropland. Addition of biochar to soils was placed here because biochar can be added to all land uses even if it typically associated with agricultural practices. Where restoration of degraded ecosystems occurs, such as for peatlands and coastal wetlands, mitigation is achieved by enhancing the terrestrial carbon stocks in the form of biomass, soil organic matter, or both. Where the focus is on reducing conversion of natural ecosystems, such as peatlands, coastal wetlands, or grasslands, similar to REDD, the mitigation benefit would be achieved by deviating from scenario trajectories that are based on land-use conversion pressures from proximate and underlying drivers. Fire management and biochar addition combine different mitigation pathways, which are described below.

2.2.3.1 Restoration and reduced conversion of peatlands

Peat restoration involves bringing degraded or drained peatlands back to (semi-)natural forms through abandoning management practices and rewetting. This process stops the mineralization of organic matter (subsidence) and emissions of N_2O while increasing the carbon sink (Smith *et al.*, 2019). However, restoration can increase CH_4 emissions, particularly in nutrient-rich fens. Besides their very large mitigation potential due to large carbon stocks, peatland restoration also provides numerous benefits for biodiversity and ecosystem services, as well as adaptation benefits to downstream flooding by buffering water flow and peak runoff (see Table 2.3 for additional details). While there is a possibility of peatland restoration causing local displacement of food production on agriculturally used peat soils, the effect is limited in scale due to the relatively small areas affected and can therefore likely be buffered through social measures (Smith *et al.*, 2019). Within the NGHGI, mitigation via peatland restoration can be described as changes in SOM and biomass through land-use change, as well as possible changes in CH_4 and N_2O emissions after rewetting.

Similar to REDD+, reducing the conversion of peatlands would maintain existing carbon stocks and all other environmental, economic, and social benefits and could be achieved by addressing the drivers leading to their conversion. Reporting within the NGHGI would thus occur by deviating from an assumed baseline scenario of GHG emissions resulting from peatland conversion.

2.2.3.2 Fire management

Fire management is primarily intended to protect lives and assets through prevention, detection, control, restriction, and suppression of fire (Smith *et al.*, 2019). In the context of forest management, it also includes prescribed burning and management of fire regimes and can be used to prevent uncontrolled wildfires thereby avoiding the emissions of CO_2, CH_4, and N_2O, next to a wide range of other gases and smoke aerosols with significant health impacts (Smith *et al.*, 2019). Additional information is provided in Table 2.2. In the context of the NGHGI, fire management can be reflected as avoided losses of biomass, changes in the emission of CH_4 and N_2O from cropland and grasslands, as well as possible changes in crop residues.

2.2.3.3 Restoration and reduced conversion of coastal wetlands

Restoration of coastal wetlands involves returning degraded mangroves, salt marshes, and seagrass ecosystems back to (semi-)natural states (Smith *et al.*, 2019). This can increase carbon sinks and the provision of multiple ecosystem services next to coastal protection against storm and flood risks as well as breeding and nursery grounds for a wide range of economically important marine species and thereby provides significant benefits to ecosystem resilience and adaptation (Smith *et al.*, 2019; UNESCO, 2020). See Table 2.3 for additional information. Within the NGHGI coastal wetland restoration can be reported as changes in biomass and SOM due to land-use change.

2.2.3.4 Biochar addition to soil

Adding biochar, a solid pyrolysis product from wood or other plant residues, to soils can enhance their water holding capacity and often increases soil fertility while potentially changing N_2O emission rates (Mbow *et al.*, 2019; Smith *et al.*, 2019). However, availability of biochar depends on large amounts of unused plant residues or wood by-products if it is not to compete with other uses of biomass and can therefore potentially result in indirect land-use change where biochar production is carried out without care (see Table 2.3 for additional information). Where such biomaterials exist, biochar may be a useful soil supplement with long-term benefits for soil fertility and potentially significant mitigation potentials. Within the context of the NGHGI, biochar additions can be reported as changes in SOM in soils and, potentially, changes in N_2O emissions.

2.2.3.5 Reduced grassland conversion to cropland

In the process of converting grassland into cropland, large soil carbon stocks are typically mineralized and released into the atmosphere (Smith *et al.*, 2019). Reducing conversion can therefore contribute to climate change mitigation by keeping SOM locked up in the soils. Keeping grassland soils intact also reduces erosion and land degradation and enhances resilience to climate change through more adapted species and may also improve soil water-holding capacity and biodiversity (Smith *et al.*, 2019). See Table 2.23 for additional information. Similar to other contexts where mitigation is achieved by avoiding change from happening, reducing grassland conversion to cropland can be reported in the NGHGI as a deviation from an anticipated baseline trajectory of emissions from changes in SOM and biomass through land-use change.

Box 2.5.The Sustainable Livestock Nationally Appropriate Mitigation Action of Honduras.
As part of its Technology Needs Assessment, Honduras has given priority to sustainable livestock production to increase its cattle population, which has recently suffered from the impacts of a series of hurricanes. In addition, the expansion of the palm tree plantations is reducing the area available for pasture or directly leading to the transformation of pasture into cropland. The Sustainable Livestock Nationally Appropriate Mitigation Action is part of Honduras's Technology Action Plan and focuses on the improvement of animal nutrition through measures such as fodder banks, genetic improvements, and animal health through veterinary programs. It also addresses strategies to promote livestock repopulation through improved farming systems. Source: (UNFCCC, 2017)

2.3 Identifying and selecting specific mitigation actions in the AFOLU sector

Achieving mitigation outcomes in the AFOLU sector is not straightforward given multiple demands to land. For instance, afforestation, reforestation (A/R), or the integration of trees into crop or livestock systems (agroforestry) will enhance the biomass stock, but if not implemented well they could lead to knock-on effects, such as shifting agricultural production to other places (leakage) or reductions in the availability of water (Smith *et al.*, 2019). To achieve mitigation benefits without these or other trade-offs therefore requires taking a broader perspective of the land sector that includes AFOLU but also connected sectors, such as water or energy, and the preservation of nature for the provision of ecosystem services and biodiversity (Smith *et al.*, 2014, 2019; Pörtner *et al.*, 2021). Without taking these linked systems into account, the result could diminish, cancel, or even worsen the intended mitigation outcomes.

To that end, decision-making should focus on the opportunities for achieving mitigation goals on the ground that lead to the greatest mitigation benefits at the lowest costs while providing as many co-benefits as possible. As an example, based on such considerations, Paustian *et al.* (2016) developed a decision tree that allows to identify which mitigation options to implement on agricultural lands with the purpose of enhancing their soil organic matter content, which is central to soil fertility and provides multiple co-benefits besides storing carbon to reduce GHG emissions from agricultural production (Figure 2.4). The decision tree does not explicitly include forestry, but it would be possible to substitute cropland for forest land with minor modifications to cater for the specificities of forest management.

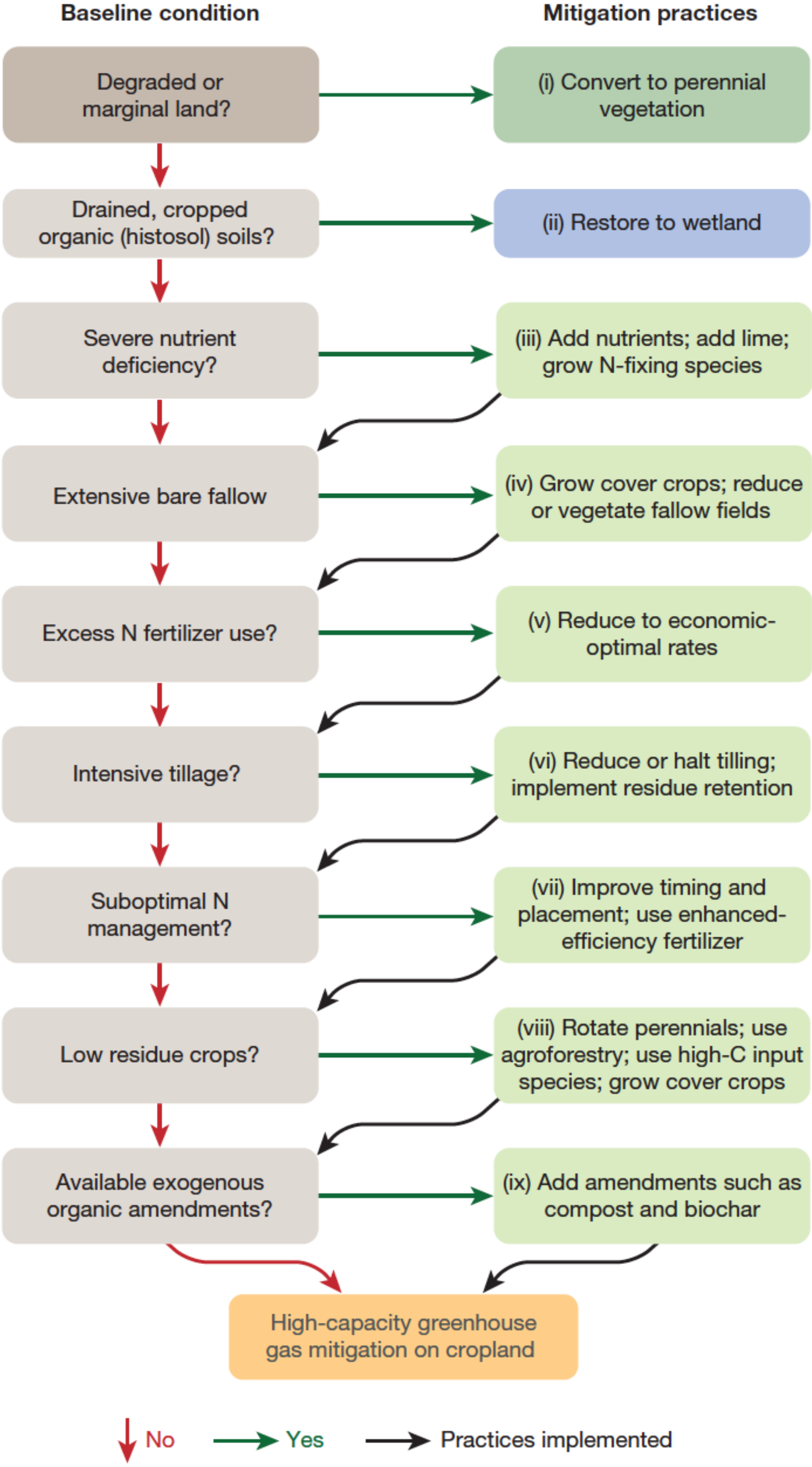

Figure 2.4. Decision tree for cropland GHG mitigation practices (Rice is not included.) For degraded, marginal lands, the most productive mitigation option is conversion to perennial vegetation either left unmanaged or sustainably harvested to offset fossil energy use (cellulosic biofuels). Histosol is soil with very high organic matter content, such as from peat bog. For more arable lands, multiple options could be implemented sequentially or in combination, depending on management objectives, cost and other constraints. The practices shown are roughly ordered from lower-cost or higher-feasibility options to more costly interventions (bottom of figure) (Paustian et *al.*, 2016)

From the top to the bottom, the decision tree roughly follows intervention options from lower to higher costs and from higher to lower feasibility (Paustian *et al.*, 2016). Restoring degraded or marginal lands as well as agriculturally used peatlands to their natural ecosystems can return large amounts of the soil organic matter that was lost during the initial conversion of the land while improving a wide range of ecosystem services and supporting natural biodiversity, though CH_4 emissions may increase when wetlands are restored (options 1 and 2). For degraded land that is expected to remain under agricultural production, options include improving the soil fertility status through nutrients to enhance productivity and to use cover crops, in particular N-fixing species, to minimize bare fallow, which is subject to greater erosion (options 3 and 4). Where soils are excessively fertilized, reduction of N amendments to economically optimal rates as well as improved timing and placement (for example through precision farming) can reduce excess N_2O emissions and nitrate leaching (options 5 and 7). Less intensive tillage of heavily tilled soils, in particular zero tillage, is often associated with an increase in soil organic matter, but reverting back to tillage can subsequently remove the sequestered carbon again (option 6). Frequently the introduction of agroforestry practices, crop rotations, cover crops, or intercropping can enhance the production of above- and below-ground biomass in the system (option 8). Where available, adding organic amendments, such as compost or biochar, can boost soil fertility while binding organic carbon in the soils (option 9).

Table 2.1. Integrated response options with mitigation outcomes in the AFOLU sector and links to source and sink categories in national GHG inventories. Source for 'description' and 'context and caveats' (Smith *et al.*, 2019).

Integrated response option	Description	Context and caveats	Links to source and sink categories in NGHGI
Mitigation options in agriculture			
Increased food productivity	Increased food productivity arises when the output of food commodities increases per unit of input, e.g., per unit of land or water. It can be realised through many other interventions such as improved cropland, grazing land and livestock management.	Many interventions to increase food production, particularly those predicated on very large inputs of agro-chemicals, have a wide range of negative externalities leading to the proposal of sustainable intensification as a mechanism to deliver future increases in productivity that avoid these adverse outcomes. Intensification through additional input of nitrogen fertiliser, for example, would result in negative impacts on climate, soil, water and air pollution. Similarly, if implemented in a way that over-exploits the land, significant negative impacts would occur, but if achieved through sustainable intensification, and used to spare land, it could reduce the pressure on land.	• Changes in SOM of mineral and organic soils • Changes in crop residues • Changes in organic and synthetic fertilizers • Possible changes in manure management and enteric fermentation • Possible changes in CH_4 and N_2O from rice cultivation • Possible changes in land use
Improved cropland management	Improved cropland management is a collection of practices consisting of a) management of the crop: including high input carbon practices, for example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology, b) nutrient management: including optimised fertiliser application rate, fertiliser type (organic manures, compost and mineral), timing, precision application, nitrification inhibitors, c) reduced tillage intensity and residue retention, d) improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions, e) improved rice management: including water management such as mid-season drainage and improved fertilisation and residue management in paddy rice systems, and f) biochar application.	Improved cropland management can reduce GHG emissions and create soil carbon sinks, though if poorly implemented, it could increase nitrous oxide and methane emissions from nitrogen fertilisers, crop residues and organic amendments. It can improve resilience of food crop production systems to climate change, and can be used to tackle desertification and land degradation by improving sustainable land management. It can also contribute to food security by closing crop yield gaps to increase food productivity.	• Changes in SOM of mineral and organic soils • Changes in crop residues • Changes in organic and synthetic fertilizers • Possible changes in CH_4 and N_2O from rice cultivation • Possible changes in biomass through set-side and land-use change
Improved grazing land management	Improved grazing land management is a collection of practices consisting of a) management of vegetation: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management, b) animal management: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification, and c) fire management: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning. (see also fire management as a separate response option)	Improved grazing land management can increase soil carbon sinks, reduce GHG emissions, improve the resilience of grazing lands to future climate change, help reduce desertification and land degradation by optimising stocking density and reducing overgrazing, and can enhance food security through improved productivity.	• Changes in SOM of mineral and organic soils • Changes in organic and synthetic fertilizers • Changes in manure remaining on grazing land • Possible changes in biomass through set-side and land-use change
Increased soil organic carbon content	Practices that increase soil organic matter content include a) land-use change to an ecosystem with higher equilibrium soil carbon levels (e.g., from cropland to forest), b) management of the vegetation: including high input carbon practices, for example, improved varieties, rotations and cover crops, perennial cropping systems, biotechnology to increase	Increasing soil carbon stocks removes CO_2 from the atmosphere and increases the water-holding capacity of the soil, thereby conferring resilience to climate change and enhancing adaptation capacity. It is a key strategy for addressing both desertification and land degradation. There is some evidence that crop yields and yield stability increase by increased organic matter content, though	• Changes in SOM of mineral and organic soils through application of manure, crop residues, biochar, etc.

	inputs and recalcitrance of below ground carbon, c) nutrient management and organic material input to increase carbon returns to the soil, including: optimised fertiliser and organic material application rate, type, timing and precision application, d) reduced tillage intensity and residue retention, and e) improved water management: including irrigation in arid/semi-arid conditions.	some studies show equivocal impacts. Some practices to increase soil organic matter stocks vary in their efficacy. For example, the impact of no-till farming and conservation agriculture on soil carbon stocks is often positive, but can be neutral or even negative, depending on the amount of crop residues returned to the soil. If soil organic carbon stocks were increased by increasing fertiliser inputs to increase productivity, emissions of nitrous oxide from fertiliser use could offset any climate benefits arising from carbon sinks. Similarly, if any yield penalty is incurred from practices aimed at increasing soil organic carbon stocks (e.g., through extensification), emissions could be increased through indirect land-use change, and there could also be adverse side effects on food security.	• Changes in SOM of mineral and organic soils through tillage and water management • Changes in biomass through set-side and land-use change
Improved livestock management	Improved livestock management is a collection of practices consisting of a) improved feed and dietary additives (e.g., bioactive compounds, fats), used to increase productivity and reduce emissions from enteric fermentation; b) breeding (e.g., breeds with higher productivity or reduced emissions from enteric fermentation), c) herd management, including decreasing neo-natal mortality, improving sanitary conditions, animal health and herd renewal, and diversifying animal species, d) emerging technologies (of which some are not legally authorised in several countries) such as propionate enhancers, nitrate and sulphate supplements, archaea inhibitors and archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics, ionophores/antibiotics; and e) improved manure management, including 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.	Improved livestock management can reduce GHG emissions, particularly from enteric methane and manure management. It can improve the resilience of livestock production systems to climate change by breeding better adapted livestock. It can help with desertification and land degradation, e.g., through use of more efficient and adapted breeds to allow reduced stocking densities. Improved livestock sector productivity can also increase food production.	• Changes in CH_4 emissions from enteric fermentation through feeding, breeding, animal health, herd management, etc. • Changes in CH_4 and N_2O emissions from manure management • Potentially changes in biomass and SOM through set-side and land-use change
Agroforestry	Agroforestry involves the deliberate planting of trees in croplands and silvo-pastoral systems.	Agroforestry sequesters carbon in vegetation and soils. The use of leguminous trees can enhance biological nitrogen fixation and resilience to climate change. Soil improvement and the provision of perennial vegetation can help to address desertification and land degradation. Agroforestry can increase agricultural productivity, with benefits for food security. Additionally, agroforestry can enable payments to farmers for ecosystem services and reduce vulnerability to climate shocks.	• Changes in biomass (above and below ground) due to integration of trees into cropland and pastures • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Mitigation options on forest land			
Reforestation and forest restoration	Reforestation is the conversion to forest of land that has previously contained forests but that has been converted to some other use. Forest restoration refers to practices aimed at regaining ecological integrity in a deforested or degraded forest landscape. As such, it could fall under reforestation if it were re-establishing trees where they have been lost, or under forest management if it were restoring forests where not all trees have been lost. For practical reasons, here forest restoration is treated together with reforestation.	Reforestation is similar to afforestation with respect to the co-benefits and adverse side effects among climate change mitigation, adaptation, desertification, land degradation and food security (see row on Afforestation below). Forest restoration can increase terrestrial carbon stocks in deforested or degraded forest landscapes and can offer many co-benefits in terms of increased resilience of forests to climate change, enhanced connectivity between forest areas and conservation of biodiversity hotspots. Forest restoration may threaten livelihoods and local access to land if subsistence agriculture is targeted.	• Changes in biomass (above and below ground) due to reforestation and forest restoration • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils

Afforestation	Afforestation is the conversion to forest of land that historically have not contained forests. (see also 'reforestation')	Afforestation increases terrestrial carbon stocks but can also change the physical properties of land surfaces, such as surface albedo and evapotranspiration with implications for local and global climate. In the tropics, enhanced evapotranspiration cools surface temperatures, reinforcing the climate benefits of CO_2 sequestration in trees. At high latitudes and in areas affected by seasonal snow cover, the decrease in surface albedo after afforestation becomes dominant and causes an annual average warming that counteracts carbon benefits. Net biophysical effects on regional climate from afforestation is seasonal and can reduce the frequency of climate extremes, such as heat waves, improving adaptation to climate change and reducing the vulnerability of people and ecosystems. Afforestation helps to address land degradation and desertification, as forests tend to maintain water quality by reducing runoff, trapping sediments and nutrients, and improving groundwater recharge. However, food security could be hampered since an increase in global forest area can increase food prices through land competition. Other adverse side effects occur when afforestation is based on non-native species, especially with the risks related to the spread of exotic fast-growing tree species. For example, exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability, particularly in dry regions.	• Changes in biomass (above and below ground) due to afforestation • Changes in biomass through land-use change • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Reduced deforestation and degradation	Reduced deforestation and forest degradation includes conservation of existing carbon pools in forest vegetation and soil 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), also through establishing protected areas, improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification.	Reducing deforestation and forest degradation is a major strategy to reduce global GHG emissions. The combination of reduced GHG emissions and biophysical effects results in a large climate mitigation effect, with benefits also at local level. Reduced deforestation preserves biodiversity and ecosystem services more efficiently and at lower costs than afforestation/reforestation. Efforts to reduce deforestation and forest degradation may have potential adverse side effects, for example, reducing availability of land for farming, restricting the rights and access of local people to forest resources (e.g., firewood), or increasing the dependence of local people to insecure external funding.	• Changes in biomass (above and below ground) due to avoided deforestation and forest degradation • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils
Improved forest management	Forest management refers to management interventions in forests for the purpose of climate change mitigation. It includes a wide variety of practices affecting the growth of trees and the biomass removed, including improved regeneration (natural or artificial) and a better schedule, intensity and execution of operations (thinning, selective logging, final cut, reduced impact logging, etc.). 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.	Sustainable forest management can enhance the carbon stock in biomass, dead organic matter, and soil – while providing wood-based products to reduce emissions in other sectors through material and energy substitution. A trade-off exists between different management strategies: higher harvest decreases the carbon in the forest biomass in the short term but increases the carbon in wood products and the potential for substitution effects. Sustainable forest management, also through close-to-nature silvicultural techniques, can potentially offer many co-benefits in terms of climate change mitigation, adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection, coastal area protection and water and flood regulation. Forest management strategies aimed at increasing the biomass stock levels may have adverse side effects, such as decreasing the stand-level structural complexity, biodiversity and resilience to natural disasters. Forest management also affects albedo and evapotranspiration.	• Changes in biomass (above and below ground) due to forest management and restoration • Changes in harvested wood products (HWP) • Possible changes in SOM of mineral and organic soils • Potentially changes in biomass and SOM through set-side and land-use change

Mitigation options in all/other land uses			
Restoration and reduced conversion of peatlands	Peatland restoration involves restoring degraded/ damaged peatlands, which both increases carbon sinks, but also avoids ongoing CO_2 emissions from degraded peatlands. So, as well as protecting biodiversity, it both prevents future emissions and creates a sink.	Avoided peat impacts and peatland restoration can provide significant mitigation, though restoration can lead to an increase in methane emissions, particularly in nutrient rich fens. There may also be benefits for climate adaptation by regulating water flow and preventing downstream flooding. Considering that large areas of global peatlands are degraded, peatland restoration is a key tool in addressing land degradation. Since large areas of tropical peatlands and some northern peatlands have been drained and cleared for food production, their restoration could displace food production and damage local food supply, potentially leading to adverse impacts on food security locally, though the global impact would be limited due to the relatively small areas affected.	• Changes in SOM of organic soils due to land-use change • Changes in biomass through land-use change • Possible changes in CH_4 and N_2O due to peatland restoration
Fire management	Fire management is a land management option aimed at safeguarding life, property and resources through the prevention, detection, control, restriction and suppression of fire in forest and other vegetation. It includes the improved use of fire for sustainable forestry management, including wildfire prevention and prescribed burning. Prescribed burning is used to reduce the risk of large, uncontrollable fires in forest areas, and controlled burning is among the most effective and economic methods of reducing fire danger and stimulating natural reforestation under the forest canopy and after clear felling.	The frequency and severity of large wildfires have increased around the globe in recent decades, which has impacted on forest carbon budgets. Fire can cause various GHG emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and others such as carbon monoxide (CO), volatile organic carbon, and smoke aerosols. Fire management can reduce GHG emissions and can reduce haze pollution, which has significant health and economic impacts. Fire management helps to prevent soil erosion and land degradation and is used in rangelands to conserve biodiversity and to enhance forage quality.	• Changes in biomass through fire management • Changes in the emission of CH_4 and N_2O due to reduced fires on cropland and grasslands • Possible changes in crop residues
Restoration and reduced conversion of coastal wetlands	Coastal wetland restoration involves restoring degraded/ damaged coastal wetlands, including mangroves, salt marshes and seagrass ecosystems.	Coastal wetland restoration and avoided coastal wetland impacts have the capacity to increase carbon sinks and can provide benefits by regulating water flow and preventing downstream flooding. Coastal wetlands provide a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments. Since large areas of global coastal wetlands are degraded, restoration could provide benefits land degradation. Since some areas of coastal wetlands are used for food production, restoration could displace food production and damage local food supply (Section 6.3.4), though some forms (e.g., mangrove restoration) can improve local fisheries.	• Changes in SOM of soils due to land-use change • Changes in biomass through land-use change
Biochar addition to soil	The use of biochar, a solid product of the pyrolysis process, as a soil amendment increases the water-holding capacity of soil. It may therefore provide better access to water and nutrients for crops and other vegetation types (so can form part of cropland, grazing land and forest management).	The use of biochar increases carbon stocks in the soil. It can enhance yields in the tropics (but less so in temperate regions), thereby benefitting both adaptation and food security. Since it can improve soil water-holding capacity and nutrient-use efficiency, and can ameliorate heavy metal pollution and other impacts, it can benefit desertification and land degradation. The positive impacts could be tempered by additional pressure on land if large quantities of biomass are required as feedstock for biochar production.	• Changes in SOM of mineral soils • Possible changes in N_2O emissions from fertilizers
Reduced grassland conversion to cropland	Grasslands can be converted to croplands by ploughing of grassland and seeding with crops. Since croplands have a lower soil carbon content than grasslands and are also more prone to erosion than grasslands, reducing conversion of grassland to croplands will prevent soil carbon losses by oxidation and soil loss through erosion. These processes can be reduced if the rate of grassland conversion to cropland is reduced.	Stabilising soils by retaining grass cover also improves resilience, benefitting adaptation, desertification and land degradation. Since conversion of grassland to cropland usually occurs to remedy food security challenges, food security could be adversely affected, since more land is required to produce human food from livestock products on grassland than from crops on cropland.	• Changes in SOM of mineral and organic soils through land-use change • Changes in biomass through land-use change

3 Strategies for policy development and implementation

The chapter discusses setting targets for climate action in the AFOLU sector in the context of sustainable land management. This is important in order to frame mitigation options while bearing national development goals and the SDGs in mind. This wider context is necessary considering the connections to other interests and sectors related to demands on land and the limitations and constraints imposed by finite natural resources and the need to preserve nature to keep ecosystem services underpinning human activities intact (IPCC, 2019b; Pörtner *et al.*, 2021). Identifying ways through which to prioritize between multiple competing demands to land can therefore help enhance synergies and limit trade-offs. Considering the challenges related to increasing integration across sectors and levels of government, the chapter will then discuss issues related to governance and implementation of policies and measures to support decision-making.

Box 2.1.Swaziland's Eco-Lubombo Biosphere project.
Agriculture, and livestock in particular, is the main economic sector in Swaziland. Climate change-related factors, such as the alteration of rain patterns and the increasingly frequent droughts, are negatively affecting crop production. In addition, drivers such as population growth are increasing the drainage of wetlands to create new farmland or build roads and enhancing the deforestation of forests. As a result of the conclusions from Swaziland's Technology Action Plan for mitigation and adaptation, it was decided to add several new AFOLU-related technologies to the already existing UNESCO-supported Eco-Lubombo Biosphere project. Among others, the project includes the development of a National Wetland Policy, an eco-trail programme to develop sustainable tourism, and agroforestry initiatives. Source: (UNFCCC, 2017)

3.1 Raising ambitions for climate action in the AFOLU sector

The Paris Agreement foresees that countries increase their ambitions to tackle climate change over time to ensure that Parties' combined targets are continually more stringent, raising the prospect of achieving the collective mitigation and adaptation goals (UNFCCC, 2016). However, countries have been slow in raising their ambitions, and the current trajectory of implementing all nationally determined contributions (NDCs) would lead to ca. 3°C above pre-industrial levels – significantly above the Paris Agreement goal (UNEP, 2020).

Considering the sector's large contribution to climate change globally and its relevance to national income and food security, a wide range of countries are now seeking to align national development targets with climate goals by including the AFOLU sector in their national mitigation strategies. Over 90% of countries (out of 188 at the time of publication) have included AFOLU in their NDCs related to mitigation (and/or adaptation), and many highlight the sector's relevance for synergies between adaptation and mitigation (FAO, 2016). According to Grassi *et al.* (2017), about a quarter of planned emission reductions globally are in land use, land-use change and forestry (LULUCF). The opportunities of the sector to contribute to food security are also explicitly recognized such that 31 countries included climate-smart agriculture in their NDCs in order to address food security, mitigation and adaptation concomitantly (FAO, 2016).

Box 3.2. The nexus framing as a means of capturing the multidimensionality of land.

Although integrated management of land has long been considered important, describing the interrelations between a range of sectors and connected topics within a water-energy-food nexus has gained significant traction over the past decade (Wichelns, 2017; Zhang *et al.*, 2019). Core to the large majority of the nexus literature is the understanding that demands to land, including the needs for food, water, energy, and shelter, among others, are typically addressed in isolation and without consideration of concurrent demands to land (Conway *et al.*, 2015; Leck *et al.*, 2015; Keairns *et al.*, 2016; Kurian, 2017; Weitz *et al.*, 2017; Wichelns, 2017; de Amorim *et al.*, 2018; Nhamo *et al.*, 2018; Mercure *et al.*, 2019; Xu *et al.*, 2019). This can lead to a situation where more land would be required to meet all these demands than is available without exceeding its carrying capacity. Exogenous trends, such as population growth, urbanization, and changing diets can add additional pressures on the finite land resource, pushing the system further beyond sustainability limits (Steffen *et al.*, 2015; Obersteiner *et al.*, 2016; Campbell *et al.*, 2017; OECD, 2017; Conijn *et al.*, 2018; D'Odorico *et al.*, 2018; de Amorim *et al.*, 2018). Climate change will further exacerbate these pressures, for instance due to reductions in ecosystem productivity or carbon storage (Froese *et al.*, 2019; Smith *et al.*, 2019).

Underlying the nexus framing is a more holistic perspective of the natural resource base, which includes land, water, energy, capital, and labour and recognizes the different objectives and needs of people amidst their environments (FAO, 2014). Figure 3.2 provides a conceptual representation of how these needs interfere with and are shaped by driving forces, which can be global to local in nature, and can have large effects on the resource base. Organizing this complex set of interrelations in ways that meet the diverging interests and goals of stakeholders is critical to the long-term sustainable management of the natural resource base, including achieving mitigation in the AFOLU sector (FAO, 2014a). Addressing the multiple demands to land together is therefore believed to lead to better results with greater synergies and less trade-offs (Leck *et al.*, 2015; Obersteiner *et al.*, 2016; D'Odorico *et al.*, 2018; Soto Golcher *et al.*, 2018; Froese *et al.*, 2019; Momblanch *et al.*, 2019). While the majority of the literature focuses on water, energy, and food, reflecting fundamental human needs, other elements, such as forests or ecosystems, are often added (Obersteiner *et al.*, 2016; Melo *et al.*, 2020).

Despite broad agreement on the multiple benefits of integrated solutions, the nexus concept has also been criticized. The main arguments refer to: (1) not sufficiently capturing the complexities between the nexus dimensions (Weitz *et al.*, 2017); (2) frequently not considering the time, costs, and challenges of coordination and cooperation (Wichelns, 2017); (3) being overly technology focused and insufficiently aware of the political economy in which progress toward more integrated solutions could take place (Leck *et al.*, 2015); (4) often lacking sufficient temporal or spatial data to capture the interactions between natural and social processes (Shannak *et al.*, 2018); (5) being disconnected from decision-making and policy processes because it lacks insights on the conditions for collaboration and coordination across sectors, including external dynamics and political and cognitive factors determining change (Weitz *et al.*, 2017); and (6) being altogether conceptually inconclusive for lacking a coherent framework against which to assess results and observations (Cairns *et al.*, 2016; Wichelns, 2017).

Underlying the Water-Energy-Food Nexus approach of FAO is a holistic vision of sustainability that recognises and tries to strike balance between the different goals, interests and needs of people and the environment. It explicitly addresses complex interactions and feedback between human and natural systems. The resource base refers to both natural and socio-economic resources, on which we depend to achieve different goals and interests pertaining to water, energy and food. Nexus interactions are about how we use and manage resource systems, describing interdependencies (depending on each other), constraints (imposing conditions or trade-offs) and synergies (mutually reinforcing or having shared benefits). Interactions take place within the context of globally relevant drivers, such as demographic changes, urbanisation, industrial development, agricultural modernisation, international and regional trade, markets and prices, technological advancements, diversification and changes of diets, and climate change as well as more context-specific drivers, like governance structures and processes, cultural and societal beliefs and behaviours. These drivers often have a strong impact on the resources base, causing environmental degradation and resource scarcity, but they also affect and are affected by different social, economic and environmental goals and interests (FAO, 2014b).

To achieve greater integration and coordination across sectors and levels of decision-making than is typical of most current contexts, Weitz *et al.* (2017) suggest to: (1) reimagine nexus boundaries to include other sectors and scales; (2) elaborate on shared, contextual principles to guide the negotiation of trade-offs; and (3) view policy coherence as a learning process of changing values and mindsets rather than a technicality.

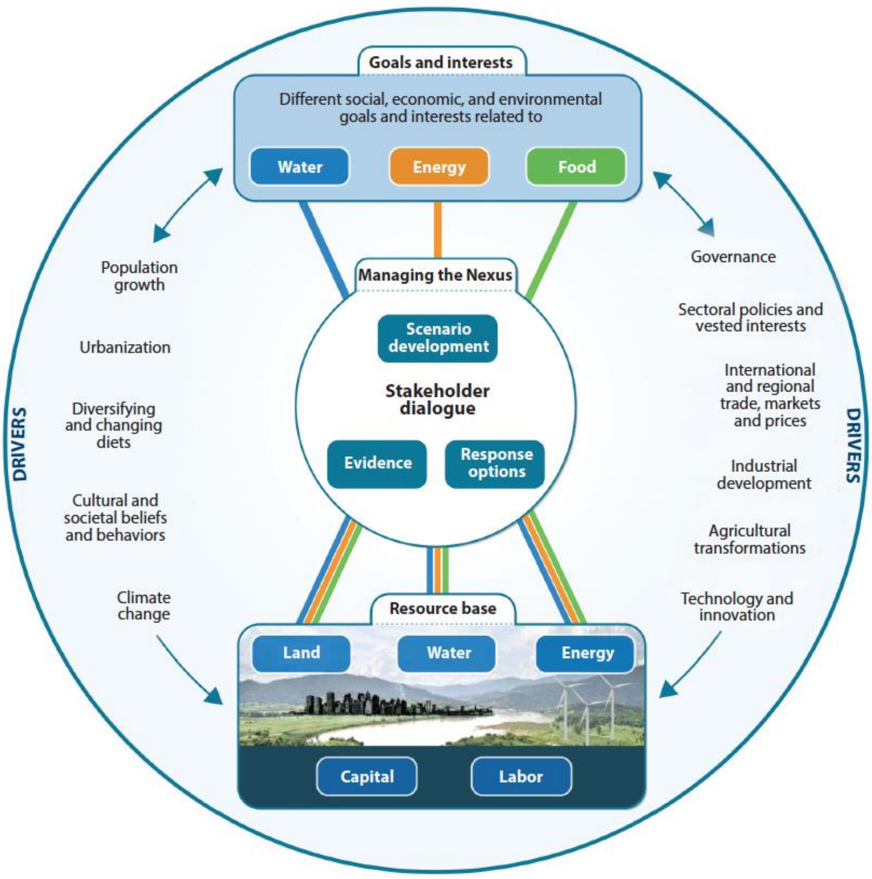

Figure 3.1.The FAO approach to the Water-Energy-Food Nexus.

3.2 Land-use planning within finite resources

Considering that introducing mitigation measures in the AFOLU sector often impinges on existing forms of land use and can affect the ecosystem services a given area of land provides, there is a need to take a broader perspective to land-use planning and management of resources that takes existing economic, sociocultural, and environmental dimensions into account. While there is often scope for collaboration to meet political, economic, environmental, and social objectives, there are also limits to reaching agreements that are acceptable to all stakeholders involved. To minimize conflict among relevant stakeholders, their participation in the planning process is therefore crucial and can potentially identify important synergies and avoid many trade-offs (Kongsager *et al.*, 2015; Liu *et al.*, 2018; Shannak *et al.*, 2018; Soto Golcher *et al.*, 2018; Mercure *et al.*, 2019; Momblanch *et al.*, 2019; Smucker *et al.*, 2020; Di Sacco *et al.*, 2021; Kissinger *et al.*, 2021). As there are no entirely objective criteria for identifying land use preferences, an important component of successful stakeholder negotiations could be to agree on the approaches to prioritize demands to land (Fischer *et al.*, 2007; Garnett *et al.*, 2015; Fritsche *et al.*, 2020; Muscat *et al.*, 2020; Benton *et al.*, 2021; Di Sacco *et al.*, 2021).

The systematic review by Muscat *et al.* (2020) might serve as an example of how different demands for food, feed and fuel production on finite land resources could be prioritized. They reviewed competition for biomass and resources such as land, water, labour, and capital and identified 7 interactions that determine the effective use of biomass and their associated synergies and trade-offs: 1) biomass demand; 2) crop yields (per unit land); 3) human-edible feed; 4) animal-based food in human diets; 5) food supply-chain efficiency; 6) type of bioenergy feedstock; and 7) implementation of land-use policies. Based on these findings, Muscat *et al.* (2020) propose a framework for an effective use of biomass that relies on cascading principles to use resources for food first, avoid losses and recycle waste back into the system as feed or fuel, and use livestock to enhance the value of biomass not available to humans (Figure 3.1).

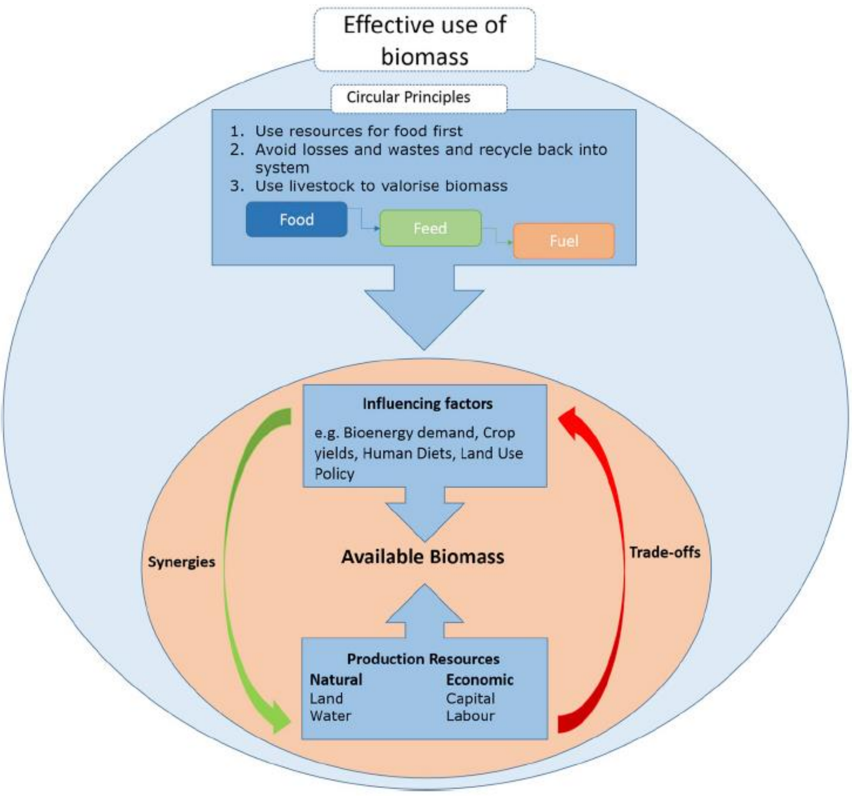

Figure 3.2. Example of a prioritization framework for decision-making in the AFOLU sector (Muscat *et al.*, 2020)

In addition to finding ways to ensure that finite land resources can maintain their ecological functions while meeting societal needs, an important question in the context of land-use planning is the identification of appropriate instruments to achieve mitigation goals. For instance, the Special Report on Climate Change and Land provides a list of instruments that could support achieving the Paris Agreement's temperature goal (Van Vuuren et al. 2017b and O'Neill et al. 2017 in: Hurlbert *et al.*, 2019). Many of the instruments listed below (and taken verbatim from the report) rely on principles that manage land as a finite resource and therefore can be utilized to allocate land uses effectively, efficiently, and often more equitably. The instruments listed subsequently are not comprehensive and are merely presented to incentivize reflections on what can be done in support of climate action in the AFOLU sector. While the list encompasses instruments that go beyond the AFOLU sector, they can all have effects on it. Finally, no discussion on the effectiveness of the instruments or best practices for the sector is provided as the results are strongly dependent on the contexts in which they are applied.

The instruments included in the Special Report on Climate Change and Land are: "effective carbon pricing, emission trading schemes (including net CO_2 emissions from agriculture), carbon taxes, regulations limiting GHG emissions and air pollution, forest conservation (mix of land sharing and land sparing) through participation, incentives for ecosystem services and secure tenure, and protecting the environment, microfinance, crop and livelihood insurance, agriculture extension services, agricultural production subsidies, low export tax and import tariff rates on agricultural goods, dietary awareness campaigns, taxes on and regulations to reduce food waste, improved shelf life, sugar/fat taxes, and instruments supporting sustainable land management, including payment for ecosystem services, land-use zoning, REDD+, standards and certification for sustainable biomass production practices, legal reforms on land ownership and access, legal aid, legal education, including reframing these policies as entitlements for women and small agricultural produces (rather than sustainability)." (Hurlbert *et al.*, 2019).

3.3 Integrative environmental governance for decision-making

While achieving mitigation in the AFOLU sector can have significant synergies, mitigation actions in a context as complex as the AFOLU sector can also lead to significant trade-offs. To minimize possible trade-offs, interventions should be considered in the context of all possible risks. There is broad agreement that this typically requires greater integration and policy coherence across sectors and governance levels with interests in and demands for land and natural resources (IPCC, 2019b; Muscat *et al.*, 2020; Pörtner *et al.*, 2021). When planning for mitigation in the AFOLU sector it is therefore very important to consider opportunities for and challenges of reaching greater integration. While achieving greater integration and policy coherence across sectors and levels of governance in the context of mitigation in the AFOLU sector requires addressing a wide range of technical issues, questions related to influencing processes to reach the desired outcomes are equally important as these come with their own challenges (Weitz *et al.*, 2017). Therefore, achieving stronger policy coherence and integration requires a deeper recognition of the conditions under which it can take place and knowledge on how to reach agreements that address valid concerns by stakeholders to achieve the desired goals.

The following reflections largely build on Weitz *et al.* (2017) who synthesize key elements of integrative environmental governance (IEG) to address the main challenges of and opportunities for enhancing integration and policy coherence. The subsequent paragraphs and Table 3.1 only provide brief insights into elements that are relevant in this context and are not specific to mitigation. They do not offer a template or specific guidance into what works where, as such issues are very context-specific and, by their very nature, difficult to frame. The main purpose of the following reflections is therefore to raise awareness of the challenges of and opportunities for developing ambitious climate action in the context of multiple demands to land. Nevertheless, despite the complexity of the matter, it is possible to somewhat structure relevant elements and articulate questions that are helpful in decision-making and negotiation processes:

- The starting point for understanding the conditions under which to achieve mitigation outcomes while minimizing possible trade-offs is an analysis of the current level of policy fragmentation, the actors involved, and their objectives.
- The second step would be to determine the level of future coordination and coherence desired to achieve the policy targets.
- The final step would be to identify under which conditions greater integration and policy coherence can be achieved.

Table 3.1 captures these three steps through reflections on a range of governance-related questions.

Step 1, political and cognitive factors as determinants of change, allows to assess the status quo and asks questions related to:

- reasons for and outcomes of different forms of policy coordination;
- existing regulatory instruments, their enforcement, and how they are interacting;
- ways through which trade-offs or societal interests are handled;
- the kind of interactions prevalent between actors;
- how rules at global levels are affecting national level governance; and
- how ecosystem boundaries and jurisdictional boundaries are interacting.

Step 2, conditions for cross-sector coordination and collaboration, examines the conditions under which future policy objectives can be agreed and the levels of policy coherence and coordination needed to achieve these goals. Relevant questions are related to:

- justification for changes to the status quo;
- key actors that need to be engaged and how to engage them;
- how the changes at national level affect subnational levels and different sectors; and
- what kind of instruments should be used.

Step 3, dynamics beyond cross-sector interactions, looks into the conditions that enable or facilitate achieving the anticipated goals as well as the obstacles and possible opportunities for solutions within policy constellations that are difficult to change. Relevant questions are related to:

- motivators for increased integration and the opportunities for creating them through appropriate governance structures;
- cognitive factors, such as trust and ownership, that enable change; and
- opportunities to achieve desired outcomes within fragmented systems.

In summary, considering the challenges in implementing even the most effective mitigation options, providing attention to the governance-related issues of implementing GHG mitigation in the AFOLU sector is critically important. For instance, even REDD+, which initially was considered an 'easy win' has faced implementation challenges, largely due to governance-related issues and drivers external to the forests that are meant to be protected (IPCC, 2019b). Creating conditions that enable greater policy coherence through integrative environmental governance is a difficult task for which there is no ready-made solution, but viewing policy coherence and integration as a learning process of changing values and mindsets rather than a technicality may help to overcome some of the challenges. This may be particularly true for the understanding that sufficient levels of coherence, rather than perfect solutions, can be politically more feasible while offering additional stability through policy overlaps and redundancies (Weitz *et al.*, 2017).

Box 3.3.Kenya's Climate Smart Agriculture Strategy 2017-2026.

Kenya envisions becoming a middle-income country by 2030, and the agriculture sector is identified as one of the key sectors to secure economic growth, ensure food security, provide raw materials for agroindustry, create employment opportunities, and generate national income. While critical to Kenya's economic success, the AFOLU sector is also responsible for a third of the country's emissions, and AFOLU emissions are expected to rise from 20 Mt CO_2e in 2010 to 27 Mt CO_2e by 2030 driven by livestock and land-use change under a business-as-usual scenario. At the same time, since 98% of agricultural production systems are rain-fed, the sector is highly susceptible to the impacts of climate change, which are expected to exacerbate, leading to more droughts and floods. The Government of Kenya has been exploring different strategies to address this situation.

The *Climate-smart agriculture* (CSA) concept was born from the acknowledgement that food security, natural resources, environment and climate change are all inextricably intertwined and cannot be considered separately anymore. Consequently, the CSA approach serves to guide actions, policies and investments to transform and reorient agricultural production systems towards climate-resilient and low carbon sustainable practices while ensuring food security and contributing to the country´s development goals. . Around this concept, the Government of Kenya, in consultation with stakeholders at county and national levels has developed the Kenya Climate Smart Agriculture Strategy 2017-2026 (KCSAS) and the Kenya Climate Smart Agriculture Implementation Framework 2018-2027 (KCSAIF) which establishes clear roles and responsibilities for all the stakeholders involved, as well as the basis for the establishment of a monitoring and evaluation framework. Implementing the KCSAS will require investments of USD 5 billion until 2026. Financial resources will be mobilized from diverse sources, and appropriate mechanisms will be established for access, disbursement, and utilization.

With the KCSAS, the Government of Kenya aims to:

- Enhance adaptive capacity and resilience of farmers, pastoralist and fisher folk to adverse impacts of climate change.
- Develop mechanisms that minimize GHG emissions from agricultural production
- Address cross-cutting issues that might adversely impact CSA.

A keystone to achieve these goals are collaborative actions amongst the various actors along the value chain, including national and county governments, farmers, the private sector, development partners, non-governmental organizations, civil society organizations and other value chain actors to leverage all possible synergies among them and avoid trade-offs. To enable this kind of collaboration the KCSAS foresees the development of a regulatory and institutional framework the sets the ground to produce CSA policies, programmes and projects in Kenya. Such a framework shall also coordinate other vital aspects in the implementation of the KCSAS, such as CSA research, data collection and the strengthening of institutional capacities.

Source: (Government of Kenya, 2017, 2018)

Table 3.1.Reflections related to integrative environmental governance in the context of enhancing policy coherence and coordination. Building on Weitz et al., (2017).

Political and cognitive factors as determinants of change	
What are the societal objectives of existing forms of policy coordination?	This question requires looking at whose interests are being addressed and for what purpose and thus implies negotiations between actors to balance differing interests in view of changing requirements or needs.
How are stated policy objectives reflected in implementation or outcome?	Strategies at the decision-making level need not translate into effective implementation and outcome. Equally, implementation will affect future decision-making. Hence, attention should be paid to all stages of the policy cycle.
What are the existing regulatory instruments and how are they enforced?	The question looks at the ways different instruments, including market-based (e.g. eco-taxes; tradable permits), soft (e.g. eco-labels; voluntary agreements), or regulatory instruments are enforced as this can strongly affect their effectiveness, efficiency, legitimacy, and equity.
How are the existing regulatory instruments interacting?	It is important to understand how regulatory instruments interact to determine questions of integration as their objectives can either: duplicate or overlap (redundancy); be devoid of regulation (lacunae or gaps); be incoherent or contradictory (conflict); or complement each other (synergy).
What are the criteria for handling trade-offs or balancing societal interests?	Answers to this question can possibly be inferred from the ways the issues are presented in public statements or policy documents based on: the priority with which they are mentioned (weight); their degree of common or shared understanding (consistency); and the level of existing efforts to realize synergies by removing contradictions and closing gaps.
What kind of interactions and modes of governance are prevalent between actors?	The engagement between and within groups of actors and institutions provides important information relative to factors determining possible integration, such as formality and interdependencies (competitive, supportive, utilitarian, normative, ideational) in relations. In addition, transparency, learning abilities, and the existence of performance-based indicators for the assessment of government policies and actions are important factors encouraging coordination and cooperation.
How are rules at global level affecting national level governance?	Rules at the global level can often be interpreted in multiple ways, potentially presenting challenges for consistent implementation at the national level and possibly at subnational levels. Global rules can also affect non-state actors operating within national frameworks in ways that are inconsistent with national governance frameworks.
How are ecosystem boundaries and jurisdictional boundaries interacting?	Natural systems, such as forests, and landscapes typically do not align with national or subnational jurisdictional boundaries and potentially lead to transboundary issues when dealing with environmental management of these systems. Examples of transboundary issues with relevance for IEG are upstream vs downstream relationships in water resource management and leakage effects in relation to REDD+ policies. Awareness of such issues will potentially reduce unintended outcomes by developing appropriate modes of collaboration and coordination.
Conditions for cross-sector coordination and collaboration	
How can changes to the status quo be justified?	In the context of mitigation in the AFOLU sector, guiding principles that balance environmental, social, and economic interests as well as short-term returns vs. long-term sustainable benefits can facilitate agreements and common understanding while also offering an opportunity to introduce new perspectives (such as setting priorities).
Who are the key actors that need to be engaged?	The answer to this question depends on the scope and scale of nexus issues at hand and includes government (at national to local levels) and non-state actors (business, civil society) as well as academia and potentially intergovernmental organizations.
What kind of collaboration is needed or desired?	Including metagovernance principles (such as inclusiveness; transparency; accountability; empowerment of weaker players; provision and access to information) into the decision-making process can facilitate making hard choices by adding bottom-up participatory approaches to top-down procedures that can enhance sensitivity to differences in social, economic, and political cultures at various levels (for example by integrating poorly represented or politically less influential stakeholders).
How will changes at the national level affect subnational level actors and vice versa?	Where power relations are asymmetrical there is a tendency for national and international regimes to increase the influence of already powerful actors that could be balanced through integrative strategies that strengthen local stakeholders' voice and ownership. Attention to vertical and horizontal policy interactions can limit unintended consequences.
What kind of instruments should be used?	Depending on the kind of integration needed, different kinds of instruments can be used to achieve the intended outcomes; these include communicative (e.g., visions and longer-term objectives), organizational (designed to alter the decision-making context, such as competences and mandates), and procedural (changing bureaucratic rules or standard operating procedures, e.g. through green procurement or environmental reporting requirements) instruments.
Dynamics beyond cross-sector interactions	
What are the motivators that enable integration?	The interactions between institutions and actors can change as a result of cognitive factors, such as the transfer of knowledge or ideas. Other motivators for seeking changes in the mode of interaction can be exchange and power-dependency. Cooperative relationships can form where those involved perceive mutual benefits by changing the status quo. On the other hand, where relationships are asymmetrical, interactions will only take place where the power-

	dependency is strong enough to induce that, but the engagement can increase when the weaker side anticipates a benefit through change. Where relationships are competitive, cooperation can improve when changing behaviour allows to mutually enhance market shares or access to resources.
How can coordination and collaboration toward integration be enhanced?	Actively managing the interactions between players can enhance integration and lead to synergies, but this comes at costs related to coordination. These costs can be minimized by introducing legal frameworks or modifying institutional arrangements (e.g., side agreements or mergers). The creation of a coordinating agency can also enhance integration. Such agencies can set standards, settle conflicts, provide incentives (carrots, sticks, or sermons), and communicate with stakeholders and other actors within society. Another mechanism that can enhance cooperation is the creation of neutral spaces for different actors to explore innovations and solutions on impartial platforms without power-dependencies.
How can cognitive factors (e.g., trust, ownership, learning) enable change?	The way options are perceived derives from value systems, different policy frames, and the ways stakeholders are informed. Changes in decision-makers' views can thus influence policies and could be addressed by reframing narratives around challenges and solutions and depend on: trust among stakeholders; sense of ownership; level of agency; and knowledge of the roles of actors in meeting challenges and opportunities. Similarly, articulating the differences in value systems can give insights into whose interests and agendas are being served can add legitimacy for policy design the instruments used.
How can fragmentation be part of the solution?	Accepting that policy design and implementation is complex, there can be benefits to fragmentation that is not conflicting at the level of key objectives. The IEG literature distinguishes between synergistic, cooperative, and conflicting fragmentation and understands that this leads to differences in costs and benefits as well as the performance against indicators of institutional effectiveness, such as speed of reaching agreements, regulatory ambition, participation of actors and sectors, and equity. As long as fundamental policy objectives are aligned, it can be said that certain levels of fragmentation can facilitate implementation and empower actors, even leading to greater resilience due to redundancies. Improving the level of synergistic fragmentation can then be achieved by enhancing transparency, levels and quality of information, communication, and institutional learning.

4 AFOLU Sector GHG inventories, baselines, monitoring and evaluating actions

Parties are required to report on the expected results of their mitigation policies, actions, and plans in terms of GHG emission reductions and removals, as well as the methodologies and approaches used to estimate such effects, in particular those influencing long-term trends in GHG emissions and removals (UNFCCC, 2019b). In this regard, one of countries' main concerns is whether the effects of the measures will be properly reflected in their national GHG inventories or not. For a country that wishes to comply with a number of GHG emissions reduction targets, mitigation measures that cannot be reflected by GHG inventories have potentially less value. This problem specially affects the AFOLU sector given the complexity and uncertainty of the methods used to calculate its GHG emissions and CO_2 removals.

Establishing whether the effects of a given mitigation action will be reflected or not in a GHG inventory and therefore whether it will be possible to measure and monitor them requires understanding how GHG inventories are compiled and how the emissions affected by the mitigation action are reported in them.

The present chapter intends to provide an overview of the principles and main steps to carry out a GHG inventory according to the Intergovernmental Panel on Climate Change 2006 Guidelines for National GHG Inventories (IPCC, 2006a), hereinafter referred as the 2006 IPCC Guidelines, and, at the same time, shed some light on its possible shortcomings. Thus, it is mainly directed at practitioners and policymakers, so that they acquire a general idea on how the compilation of GHG inventories works and may also take its limitations into consideration when assessing the effects of mitigation policies.

This chapter begins by laying out a conceptual perspective of different kinds of baselines used to measure changes in GHG emissions. The chapter then provides general methodological guidance for developing GHG inventories to account for GHG emissions and removals in the AFOLU sector according of the 2006 IPCC Guidelines. Finally, it addresses some of the limitations of GHG inventories, in particular those related to the concepts of leakage, permanence, and additionality.

4.1 Conceptual perspectives to different kinds of baselines relevant to AFOLU

Baselines, also referred to as reference scenarios, are defined as projections or estimations of how GHG emissions and removals will evolve in the future if everything continues as it is at a certain point in time (business-as-usual; BAU), i.e., if no new action intended to reduce GHG emissions or increase removals is implemented or if actions targeting the emissions are introduced. Baselines can be used to analyse trends in GHG emissions and removals, identify key categories, sectors, and activities regarding their mitigation potential, or asses the effects of plans, policies, and actions resulting in mitigation effects, i.e., reductions in GHG emissions and/or enhancements of GHG sinks. Therefore, the results of the assessment of policies, plans, and actions will be highly dependent on the baseline setting. Alternative scenarios, i.e., where mitigation actions have been undertaken to reduce GHG emissions and increase CO_2 removals will be henceforth referred to as mitigation scenarios.

Baseline setting is closely related to the development of national GHG inventories, which may be used to validate them (Novikova *et al.*, 2017), and the design and implementation of mitigation actions and their monitoring in the framework of a country's NDC. This makes it necessary to keep consistency among all these elements in terms of methodologies and data sets used.

Baselines are commonly estimated considering only absolute emissions to guarantee consistency with 2006 IPCC guidelines. However, in some specific cases emission intensities, i.e., amounts of GHG released by unit of product, land use, or services provided may also be useful to assess the effects of mitigation actions related to technology advances or productivity improvements and therefore they may also be considered for the setting of the baselines.

4.1.1 Baselines approaches and types.

There are two main methodological approaches for the estimation of baselines: bottom-up and top-down. Bottom-up approaches are based on the compilation of detailed information on technologies, land, resources, etc. as a base to capture current conditions, and are sometimes considered more suitable for the AFOLU sector (Novikova *et al.*, 2017). However, they commonly fail to reflect factors such as market interactions or price changes, among others. On the other hand, top-down approaches provide projections of future GHG emissions based on macroeconomic models using aggregated data rather than detailed and technology-specific inputs. Thus, unlike bottom-up approaches, they are able to reflect macroeconomic trends and changes, but fail to incorporate smaller and more subtle changes occurring in technology development or management practices. What follows are some of the different types of bottom-up approaches applied:

- **Static:** Here the activity data and emission factors of a given year or period of years are considered constant over the period of time the baseline will be applied to. Such an assumption renders this kind of baseline inaccurate to assess changes over long periods of time, especially in sectors as dynamic as AFOLU due to the changing demand of food and goods, where the effect of past practices on carbon dynamics does not vanish overnight. In general, this approach should only be used when there is not enough data available or when only a mere approximate estimation is required. On the other hand, since they are based on historical data, these baselines offer a low degree of ambiguity in comparison with other baselines. In any case, static baselines need to be reviewed periodically.

- **Extrapolated or dynamic:** More accurate than the static one, in this case the baseline is developed under the assumption that, if no action is implemented, current GHG emissions and removal trends, as well as those of the parameters underpinning them, will continue in the future. Therefore, the baseline is able to, at least to a certain extent, capture the influence of variations in socioeconomic circumstances or the effects of past practices or disturbances. This approach is also more data demanding than the static one but provides more realistic estimations of future scenarios and thus a more solid base on which to assess deviations in GHG emissions and removals.

- **Scenario:** Here, GHG emissions and removals are estimated for different future conditions by means of economic or other models (e.g. GLOBIOM[7]). This kind of baseline requires a higher degree of expertise and resources than the others and also requires making a number of assumptions which must be reported in a transparent way. Besides, their use may lead to inconsistencies with the historical time series, since they may not be able to reproduce historical estimations when applied to historical data. In that case, the models should undergo adjustments and modifications to ensure consistency over time.

[7] Global Biosphere Management Model: https://iiasa.ac.at/web/home/research/GLOBIOM/GLOBIOM.html

Regardless of the approach selected, the underlying methodologies and assumptions the baseline is based on can be reviewed anytime and, if there have been methodological improvements or some parameter values have been updated since the baseline was first created, it must be corrected accordingly to be consistent with the revised assumptions.

The actual development of baselines involves a number of steps similar to those of the national GHG inventories, but with some substantial differences, which, to some extent, depend on the approach selected. Thus, they also require collecting data, which shall come from a period of time which can be considered representative of the period to which the baseline is to be applied. However, there are differences in relation to the treatment of uncertainties. Instead of concentrating on addressing the main sources of uncertainty, as would be the case in GHG inventories, for baseline setting the focus of assessing and reducing uncertainty will be directed towards the areas most affected by the intended mitigation action (Penman *et al.*, 2006).

4.2 IPCC methodology for national GHG inventories

National GHG inventories account for a country's GHG emissions and CO_2 removals and are therefore a key tool to identify major emission sources, monitor the progress towards a mitigation target, or support political decision-making.

National GHG inventories cover many and very diverse economic sectors and therefore require the collaboration of several government agencies, institutions, and stakeholders. In order for this collaboration to be fruitful, roles must be clearly defined from the beginning, establishing who is to be the inventory compiler, i.e., the entity in charge of coordinating the efforts of all the participants, who puts together the materials gathered from all the sources and guarantees the quality of the results.

4.2.1 GHG Inventories general principles

The compilation of national GHG inventories based on the 2006 IPCC guidelines shall follow the latter's guiding principles (henceforth referred as TACCC) in order to guarantee its quality:

- **Transparency:** all the procedures, methods, techniques, etc. followed in each of the phases shall be clearly documented so that anyone can understand how the inventory was built and how the numbers in it were calculated.

- **Accuracy:** the figures reported in an inventory shall be neither over- nor underestimated to the extent possible.

- **Completeness:** All relevant GHG emission sources and sink categories within the boundaries of the country should be covered and, if they are not, this must be clearly stated and the reasons behind explained.

- **Consistency:** There should be a continuity in the methods used to elaborate the inventories over the years, so that the differences between them reflect actual changes in GHG fluxes rather than methodological changes[8].

- **Comparability:** For the different national inventories to be compared with each other, these should be reported according to a common system in terms of source and sink categories but also in terms of formats and templates/tables to be used.

All the methodologies, actions, and procedures oriented to achieve the fulfilment of these principles will reduce the bias and uncertainty and thus contribute to the development of high quality national GHG inventories. These are generally referred to as *good practice* in 2006 IPCC guidelines. Establishing a number of procedures such as Quality Assurance (QA), Quality Control (QC) and Verification is necessary to guarantee the fulfilment of these principles.

In addition to the TACCC, National GHG inventories are based on a few general principles:

- Only the emissions and removals occurring inside the national territory are considered (with some exceptions such as fuels, for which emissions are counted in the country where they are sold rather than in the country where the emissions occurred).
- Inventories should only cover emissions and removals derived from direct human activities. In the case of the AFOLU sector, managed lands are taken as proxy to account for all emissions and removals caused by human activities.
- The data the inventory is built on should belong to the same year as the inventory In the absence of data, adjusted figures from previous years could be used as long as the consistency requirements are fulfilled.
- Emission accounting is based on the point of production rather than on the point of consumption.

In addition to these principles, the 2006 IPCC guidelines, just like previous editions, relies in general on combining activity data and emission factors for the calculation of GHG emissions according to different methods of which the following is one of the simplest:

Emissions = Activity data * Emission factor

Where:

- ***Activity data* (AD):** Magnitude of economic activity resulting in GHG emissions and/or removals during a given period of time. E.g. tonnes of aluminium produced, tonnes of carbon consumed, kg of fertilizer used, cattle numbers, etc.

- ***Emission factor* (EF):** Refers to either GHG emissions or removals or carbon stock change per unit of a given economic activity.

This general formula can be modified under particular circumstances. For instance, a large and diverse number of GHG sources and sinks across many different locations occurring at different points in time is characteristic of the AFOLU sector and may make the introduction of other methods convenient. In such cases, 2006 IPCC guidelines may also consider, for instance, approaches like the carbon stock method to determine CO_2 emissions between carbon pools (e.g. living biomass, soil carbon, dead organic matter, etc.). On the other hand, CO_2 removals will be calculated based on

[8] This means that, if a new methodology for the estimation of GHG emissions is introduced in a certain year, all previous inventories shall be reviewed and modified to include the new methodology and therefore make the time series comparable with each other.

carbon stock differences. Hence, there are a number of rules that are only applied to the AFOLU sector:

- CO_2 emissions and removals resulting from the decay of short-lived biogenic material removed from its growing place are not to be reported since it is assumed that they will balance each other. This general rule may be disregarded if enough data is available to make more accurate estimations.

- All CO_2 emissions from the AFOLU sector will only be reported within the sector regardless of where they actually take place in order to avoid double counting. For instance, all the CO_2 emissions resulting from burning biomass for energy will be considered as AFOLU sector emissions. However, any non-CO2 emissions resulting from the same process are reported in the sectors they occur in.

- Other more sophisticated approaches may be applied for the estimation of GHG emissions and removals, such as carbon budget models to assess stocks and flows among carbon pools.[9]

4.2.2 Land representation

Building an inventory is an iterative and continually ongoing process (see Figure 4.1), where previous inventories serve as a base to new ones, and every time a new one is compiled the older ones should be renewed and updated.

[9] https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107

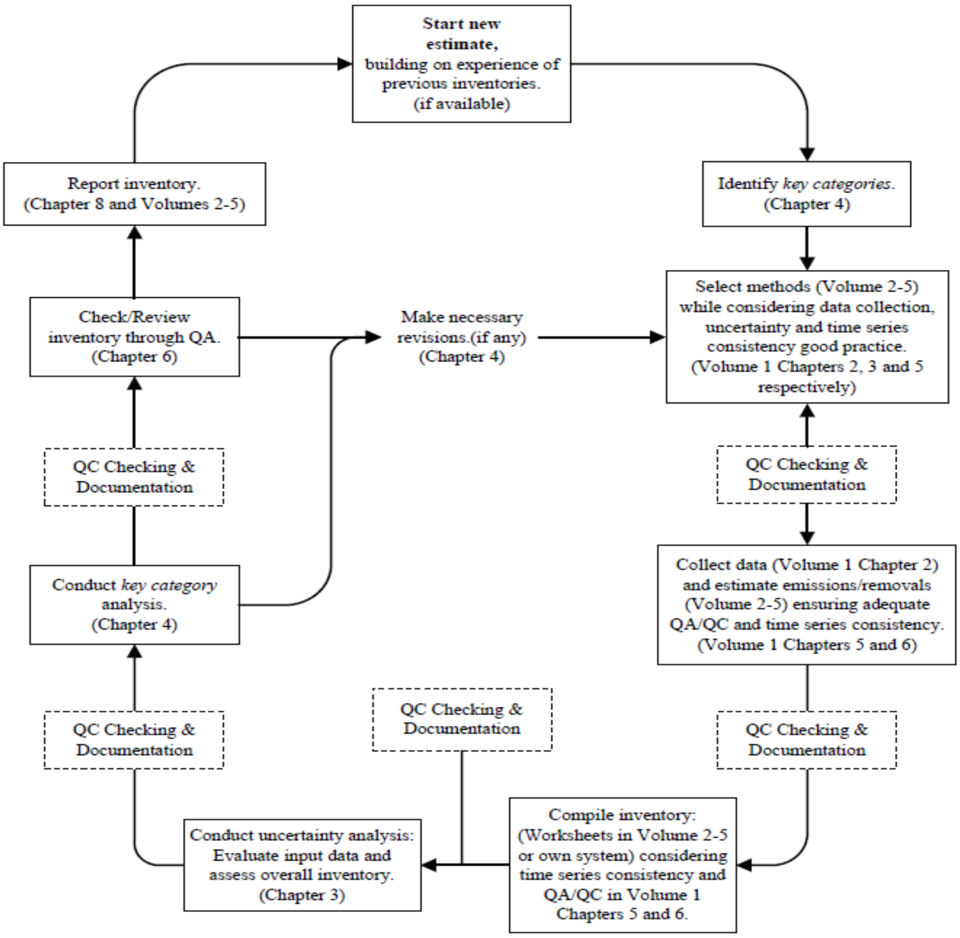

Figure 4.1.Schematic for developing GHG inventories. 2006 IPCC Guidelines Vol.1, Ch.1 (IPCC, 2006a)

Box 4.1.Monitoring, Reporting and Verification System in Uruguay.
The agro-industrial sector is one of Uruguay's economy pillars. As a consequence, the AFOLU CH_4 and NO_2 emissions represent the bulk of the country's GHG emissions. Over the years, Uruguay has established a number of climate change-related institutions, such as the National Response System to Climate Change (SNRCC), the National Environment, Water and Climate Change Office of the Presidency of the Republic (SNAACC), and the National Environmental System (SNA) through which it is possible to introduce climate change into national and subnational policies. In 2017 Uruguay passed the National Climate Change Policy (NCCP) and presented its first NDC containing specific goals for the LULUCF sector and for the food production GHG emissions intensity. In this context, a Monitoring, Reporting and Verification (MRV) system was designed to monitor NDC commitments, report progress to the UNFCCC, and enhance transparency and accountability. Whilst the GHG inventory would keep focusing on the GHG emissions and removals resulting from the NDC mitigation actions, the MRV system would also include non-GHG related measures, adaptation, and capacity building actions, among others. The MRV system has been operationalized in 2019 and since then has undergone several changes, in parallel with the

GHG inventory system. Through this, the coordination and synergies between both systems have been systematically improved.

Uruguay's MRV system includes a monitoring matrix with the NDC commitments and a set of indicators to monitor them (partially fed with information from the NGHGI), a map of actors involved in their development, and a roadmap with the implementation milestones each of them will go through. Finally, it also comprises the analysis of the costs and resource flows the measures would require for their implementation.

As for the institutional structure supporting the MRV implementation, whilst the GHG inventories are developed by the Ministry of Housing, Land Planning and Environment (MVOTMA) in collaboration with the Ministry of Livestock, Agriculture and Fisheries (MGAP), and the Ministry of Industry, Energy and Mining (MIEM), the MRV system is run by the same group developing the NDCs within the SNRCC under the coordination of MVOTMA. This strong political framework facilitates the articulation of the different climate change-related activities, effective institutional arrangements, efficient resource allocation, and the development of the required technical capacities within each of the institutions and bodies involved.

Together, the GHG and the MRV system contribute to the development of ambitious and consistent NDCs, the reinforcement of the cooperation and synergy among the different institutions dealing with climate change and, as a result, informed policymaking.

Source: (Partnership on Transparency in the Paris Agreement, 2019)

4.2.2.1 Land data gathering

There are three main methods or approaches that can be applied together or separately to obtain the required information on land use and set a land representation system. Which one will be used depends mainly on resources availability. The 2006 IPCC guidelines provide guidance to make the best use of the available data and observe TACCC principles in order to avoid problems such as the overlapping of land use types and produce a land representation system that can be actually used as a base to develop a GHG inventory.

- **Approach I:** Each land-type area is identified but no information about land use change is provided besides the net change, i.e. area of land converted to a certain land use type without specifying its origin. This leads to countries making assumptions about the land use changes which in turn may lead to the underestimation of GHG emissions and CO_2 removals (see example in Table 1).

- **Approach II:** Besides information about land types, it also covers information about specific land use changes in addition to net land use changes, i.e. it is able to provide information on the area of land converted from one to another type of land-use.

- **Approach III:** It includes together land-type and land use change information and also spatially explicit land-use change data (Land cover data sets IPCC 2006 V4 Ch.3 Annex 3A.1)

Table 4.1.Example for land-use categories using approach I, 2006 IPCC guidelines Vol.3, Chapter 4.

Land-use category/ strata	Initial area (million ha)	Final land area (million ha)	Net Change in area (million ha)	Status
Forest Land total	18	19	1	
Forest Land (Unmanaged)	5	5	0	Not include in the inventory estimates
Forest Land (template continental forest; converted to another land-use category)	7	8	1	Estimates should be prepared on the 8 million ha
Forest Land (boreal coniferous)	6	6	0	No land-use conversion. Could require stratification for different management regiments etc.
Grassland total	84	82	-2	
Grassland (Unimproved)	65	63	-2	Fall in area indicates land-use conversion. Could require stratification for different management regimes.
Grassland (Improved)	19	19	0	No land-use conversion. Could require stratification for different management regimes etc.
Cropland total	31	29	-2	Fall in area indicates land-use conversion. Could require stratification for different management regimes.
Wetlands total	0	0	0	
Settlements total	5	8	3	
Other Land total	2	2	0	Unmanaged -not in inventories estimates
Total	140	140	0	Note: areas should reconcile

The 2006 IPCC guidelines propose a land classification system with 6 broad land categories based on land-cover type, land use, or both. The exact definition of each type may vary from one country to another as long as the same land is not accounted under two different land categories or sub-categories and transparency and consistency are kept over time.

- Forest land
- Cropland
- Grassland
- Wetlands
- Settlements
- Other land

This main classification overlaps with the distinction between managed and non-managed land resulting in categories like *managed forest land* or *unmanaged grassland*, for instance.

In addition to the main land categories, if data is available and depending on the approach followed, each main land category can be subdivided into two further subcategories: *land type X remaining land type X* and *land type X converted to land type Y*. These can be further stratified according to climate zone, soil type, ecological zone, etc. to match the land types for which IPCC estimation methods are available as much as possible. In general, data availability and accuracy are the strongest limitations affecting land representation and consequently the GHG inventory results. In the AFOLU sector, a greater stratification of land use categories will improve the quality of the inventory, in particular if it is complemented with country-specific emission factors.

4.2.2.2 Land data integration

The last stage in this process would be the integration of land-use area, which here serves as activity data, with the information on carbon stocks, emission factors, and other relevant data (e.g., forest biomass stocks, average annual net increment) in order to estimate carbon stock changes and GHG emissions and removals associated to land use. The 2006 IPCC guidelines provide a step-by-step guideline on how to perform this integration, which will be implemented differently depending on the approach followed:

- **Approach I:** countries that have chosen this approach would have to choose between inferring land conversions, i.e., how much *land type X* has become *land type Y* to do the right emission factors assignation. If they decide to infer land-use changes, they will have to report how they do it. If, on the other hand, they choose not to, they will have to report the uncertainty this decision brings into the results.

- **Approach II:** countries that have chosen this approach, despite of having specific land conversion figures, would still have to infer where land use conversion took place (climate zone, soil and vegetation type, etc.), as these circumstances affect carbon stocks and emission factors. In this case too, the decision will have to be reported.

- **Approach III:** countries following this approach should be able to rightly assign carbon stocks, emission factors, and other parameters by intersecting them with the spatially explicit data on land-use type, land-use conversion, climate, soil, or management status. Some degree of inference might still be needed due to lack of data.

4.2.3 GHG Inventory compilation main steps

Once a land representation system has been set the standard GHG inventory development sequence can begin. What follows is a simplified description of the different phases of the elaboration of a GHG inventory for the AFOLU sector according to the 2006 IPCC guidelines.

4.2.3.1 Identification of key land categories

In any sector, and even more so in a sector as complex as the AFOLU sector, the first step in the development of a new inventory is the identification of the most relevant sources and sinks of GHGs within the sector in terms of absolute emissions and removals, trends and uncertainties (see decision tree in Fig.2). To do so the contributions of emissions and removals of each category to those of the total national emissions and removals must be established. In this way it is possible to prioritize the most contributing categories and allocate the available resources accordingly. Of course, key categories do not have to remain constant over the years but can change over time. The 2019 IPCC Refinement of the 2006 IPCC guidelines (IPCC, 2019a)includes some changes in the procedures followed to identify key categories.

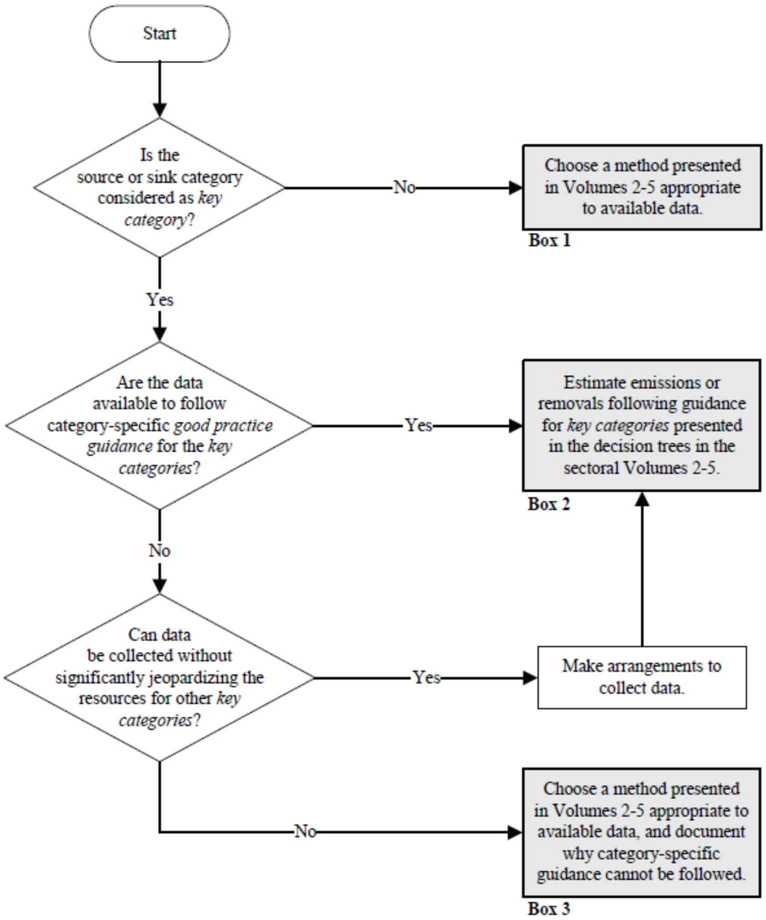

Figure 4.2. Decision tree for identification of key land categories 2006 IPCC Guidelines Vol.1, Ch.4 (IPCC, 2006a)

4.2.3.2 Method selection

After all the land has been classified and the key categories have been identified, the most suitable method to estimate GHG emissions and removals must be selected for each case (the 2019 IPCC guidelines refinement may include supplementary methodology for certain sources and sinks). The 2006 IPCC guidelines distinguish between three levels of estimation according to their complexity and data requirements:

- **Tier I:** Default methods with general parameter values suitable to be applied anywhere. The parameter values are provided by the IPCC itself and can also be found in international databases. Ideally, country-specific activity data should be used but, if none are available, global data can also be applied. As a result, the estimations made through these methods fail to capture certain changes and rarely show inter-annual variability. The 2019 IPCC Refinement includes some updates on Tier I emission factors and clarifications on the guidance for certain land-use categories.

- **Tier II:** The methods could be the same as in Tier I but the parameter values are country-, region- or even land type-specific if data is available, and therefore the estimates are more accurate and reflect better the country's specific circumstances. Since activity data has a higher temporal and spatial resolution, a wider range of source and sink categories and sub-categories can be included in the inventory.

- **Tier III:** More complex methods adapted to particular cases, including models and inventory measurement systems adapted to address national circumstances using disaggregated activity data. Higher spatial and temporal accuracy. Consequently, the resulting estimations present changes from one year to the next. The 2019 IPCC Refinement includes updates on the application of these methods.

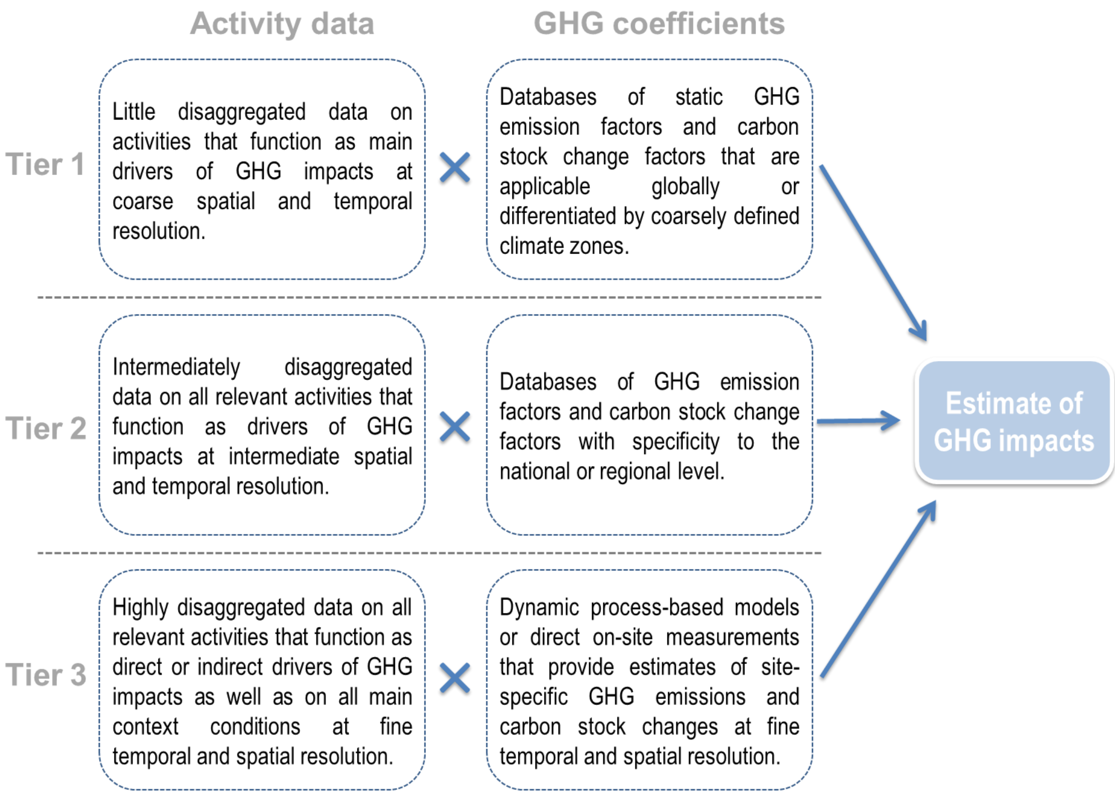

Figure 4.3.Schematic for tiered approaches (IPCC, 2006a)

For a given category, the method of choice shall be made based on the relevance of the category and the availability of data. Tier I and Tier II methods may be used by default in a preliminary phase to be substituted by Tier III methods later when enough data is available.

An alternative to the manual selection of a method for each category could be GHG calculators. These tools guide the user through the calculation of GHG emissions and removals from all covered categories using the provided AD and default EF, although in some cases more accurate ones may be introduced. Naturally, they also require land to be previously classified.

4.2.3.3 Data collection

Once the key categories have been identified and the most appropriate method tier has been assigned to each of them, the data required to carry out the estimations must be collected (EF, AD, uncertainty data, models parameters, etc.). This must be done maintaining data consistency over time and trying to minimize errors. All the processes must be checked, verified, and documented (see below for more information).

In case a certain kind of data is not available, either due to data gaps or inconsistencies in the data quality, the 2006 IPCC guidelines (Vol.1 Ch.) establish a number of methods to fill the gap, which depend on the type of data gap. If the gaps are within a mostly complete parameter time series the main methods to fill the gaps are: interpolation, extrapolation, or the use of closely connected surrogate data. On the other hand, if for a given parameter there is no data for the whole time series, some possible methods to estimate the parameter would be combining multiple data sources or using correlated proxies. Besides, in some cases, the IPCC default values may also be used.

4.2.3.4 Emissions and removals estimation

This will result from the application of the selected methodologies to the collected data. Again, consistency between the present inventory and past versions is of the utmost relevance and keeping it may require adapting previous inventories to the new methodologies. Besides, time gaps in the data also require a specific treatment to prevent them from hampering the inventory reliability. Like other previous steps, everything has to be reported in detail and subjected to a quality check.

4.2.3.5 Uncertainty analysis

The calculated estimations will then be subjected to an uncertainty analysis, which may cover all the parameters involved, and a second key category analysis will be carried out to discover categories to which a higher method may have been applied. The 2019 IPCC Refinement includes an update on uncertainty associated with activity data, in particular related to land use and forest cover surveys.

4.2.3.6 Reporting

This final step involves a last quality check and the presentation of the inventory results, methods applied, assumptions made, and all kind of useful background information in such a concise and clear way that any potential user can understand it. The 2006 IPCC guidelines provide tables, formats, and templates for this purpose.

4.2.4 Data collection and management.

In their path towards the compilation of a national GHG inventory, countries shall set up data collection schemes and procedures to obtain the data the whole inventory will eventually relay on, which makes it a key element in the development of an inventory. Regardless of the data type or the way it will be collected (direct measurements, databases, etc.), a strategy shall be established to access and collect data, prioritizing data for key categories, namely, the largest, those that may vary greatly, or those which show great uncertainty.

Data retrieving must not be a static once-in-a-while event but a dynamic process that is continually updated and improved. This requires the setting up of data flows, which in turn make it necessary to engage and find agreements with data suppliers (and closely cooperate with them). They may have valuable experience on data management and the required expertise to choose the right proxies for absent data or to select data sets that are more accurate or less prone to bias. In addition, working with data involves dealing with use restrictions and confidentiality issues. In this regard, a close cooperation with data providers (national statistical agencies for instance) is highly recommended, including setting rules for the potential use of the provided data, the way it will be made public, or the processes that can be implemented to ensure confidentiality, if needed.

The main parameters requiring a data collection set up are:

- *Emission factors (EF):* Which are generally obtained either through direct measurements or using default values from well-established databases.

- *Activity data (AD):* Which may be either generated using survey data for instance or obtained from international data sets.

- *Uncertainty data:* Regarding one of the other two main types or on any other required parameter. The 2006 IPCC guidelines recommend retrieving it along the parameter data it refers to when possible.

Further, for each of these data types there are two main ways of obtaining data: either generating it through surveys and measurements or retrieving it from already existing databases and data sets, which may have been built for other purposes. In any case, the collected data may require some adjustment or processing before being ready to be used for estimations.

- **Data retrieving/collection:** The main sources of data on inventory parameters are national statistical or regulatory agencies, experts, stakeholders, organizations, databases (see below for examples), international agencies, reference libraries, and scientific stakeholders. In addition, the IPCC offers default global and sometimes also national values for EF and other parameters, which are updated periodically. The following points list some relevant aspects to consider when retrieving data.

    - Delimiting the data request in terms of format, processing if necessary, assumptions made about the national and sectorial coverage, and updating frequency. Clearly defining these points from the start makes it much easier to update data in the future.

    - Data from national organizations is usually more up-to-date, more detailed, and its origin can be easily tracked.

    - Data from international organizations is often based on national data and, in general, is more accessible than national data. Besides, it has usually undergone an additional checking and verification process.

    - In the absence of primary data, surrogate data may also be used as long as a physical relation and a significant statistical correlation between it and the data it substitutes can be proven.

Each kind of parameter has its specificities, and some data sources may be better than others for different purposes. The table below contains some of the most common EF and AD sources for the AFOLU sector:

Table 4.2. Emissions factors and Activity data sources.

Emission factors (EF)	Activity data (AD)
IPCC Emission factors data base (EFDB)[10]	National statistics agencies and regulatory bodies
Emission regulating authority reports	FAOSTAT[11]
European Environmental Agency EMEP/CORINAR Emission Inventory Book	GLEAM[12]
USEPA International Emission Factor Database.	CORINE[13]
National laboratories	Landsat FCC[14]
OECD International Emission Factors Database	GLW[15]
Trade associations	x
Universities and research centres	x

- **Data generation:** If the required data does not exist or cannot be estimated from other existing data, it may be necessary to resort to measuring and monitoring, sampling, or surveying. These are, however, costly methods which commonly require some degree of expertise and therefore should only be applied as last resort and only for key categories. For that same reason, it is recommended to include these campaigns into already existing programs instead of creating new ones exclusively for this purpose.

  - *Surveys and census:* Although measurements could also be used, surveys are the main path to generate new activity data. They provide, together with national census, the best statistics on energy, agriculture, and production in general. However, they have some flaws; for instance, survey data may lack representativity, and census data may not be accurate enough to be used directly in the inventory but only as surrogate data. In the case of surveys, these defects may worsen if they cannot be carried out as part of an already ongoing national program[16].

  - *Measuring:* Among all the parameters required to develop an inventory, EF and abatement or destruction efficiencies are probably the ones for which measuring is more often needed. To carry them out it is recommended to use standardized methods (Penman *et al.*, 2006) to have more information on sensitivity, uncertainty, limitations and qualification instruments of known quality to ensure accuracy and calibration. Besides, attention must be paid to accurately measuring target activities, leaving out alien elements, and taking samples that cover a representative portion of the whole category. Finally, all measuring campaigns must have a protocol with a clear description of the objectives, the reporting procedures, the data processing, or how adverse situations will be handled, among other content.

In a few cases the data collected may be fed directly into the inventory. However, in most cases the retrieved data will have to undergo some processing to adapt it to the exact inventory needs. Among other processes, this may involve:

[10] http://www.ipcc-nggip.iges.or.jp/EFDB/main.php
[11] http://www.fao.org/faostat/en/#home
[12] Global Livestock Environmental Assessment Model: http://www.fao.org/gleam/en/
[13] Coordination of information on the Environment: https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster-4
[14] Landsat Forest Cover Change: http://www.landcover.org/data/landsatFCC/
[15] Gridded Livestock of the World: http://www.fao.org/livestock-systems/en/
[16] For more information on how to carry out surveys or census see 2006 IPCC guidelines Vol.1 Ch.2 sec. 2.2.5.

- *Data gap filling, updating and improvement:* The inventory consistency requirements across categories and successive versions make it necessary to avoid gaps by including the required information as soon as it is produced, updating the original data with more recent and accurate data, or completing it with data from other sources if the original data does not cover the whole country or category.

- *Numerical combination:* This may be necessary when several high-quality datasets are available for the same inventory parameter. In such a case, combining them may result in more accurate and precise data. Also, if yearly data is to be extracted from multi-year datasets or if non-calendar year data is to be corrected to represent calendar year data.

- *Regional inventory data:* If regional or sub-national datasets are available, aggregating them before feeding them into the inventory may result in better quality national inventories. Special attention must be paid to the guiding principles, in particular consistency and completeness to avoid omitting or double-counting emissions.

Box 4.2.Baseline setting for Methane Emissions from Rice Cultivation in the Philippines.

On the 6th October 2020 the CDM Executive Board, as a result of a submission by the corresponding designated national authority of the Philippines, adopted a standardized baseline for CH_4 emission factors associated to the cultivation of rice. This baseline should be valid until 19th February 2025.

The adopted baseline provides values for CH_4 emissions per hectare and season or day in continuously flooded fields without organic amendments. Out of those emission factors and by means of scaling factors that account for the differences in water regimes during the pre-season and the cultivation period and the application of organic amendments, emission factors for the fields under water management adjustment are calculated. In addition, four different cases are distinguished depending on whether the field is single or double cropping and whether it is the dry or the wet season.

The adopted baseline may be applied together with the corresponding methodology (04.0 of AMS-III.AU "*Methane emission reduction by adjusted water management practice in rice cultivation*") to projects within the Clean Development Mechanism (CDM) in general and, in particular, to projects with the goal of reducing CH_4 emissions through adjustments in water management. The adjustments typically consist of alternating continuously and intermittently flooded conditions during the cultivation period (i.e., alternating wetting and drying in single or multiple phases of aeration) in transplanted rice fields where rice straw is used as organic amendment. In the Philippines, such a modification of a rice field water regime is automatically deemed to be additional, i.e., the mitigation effects achieved are considered to be exclusively the result of the action.

Source: (UNFCCC Clean Development Mechanism, 2020)

4.3 Main land types

In addition to the general steps for the elaboration of GHG inventories described above, each land cover type, due to its own specific characteristics, presents a number of challenges when it comes to the accounting of its GHG emissions and removals.
Information on the different GHG pools in the AFOLU sector is also presented in tabulated form in Annex 2.

4.3.1 Forest Land

Forests cover approximately 31% (see Fig.1.1) of the Earth's surface and represent the world's largest CO_2 sink (Jia *et al.*, 2019). Around two thirds of the existing forests are under human management of some kind. Forest management includes a wide range of activities, from protecting forests to fuelwood gathering to commercial timber production. The 2006 IPCC Guidelines only provide guidance to estimate GHG emissions and removals from managed forest. Unmanaged forests are not considered anthropogenic GHG sources or sinks and therefore are excluded from GHG inventories, although, in some cases, they may still be affected by human activities even if the forest is not actively being managed.

Forest land can be divided, depending on the time it has been considered forest, into two main land type subcategories*: Forest Land remaining Forest Land* (FF) and *Land converted to Forest Land*. For each subcategory a different GHG accounting methodology will be applied. A 20-years interval is taken as the default time it takes for other land uses to become a forest land. If no data is available about when forest land became forest land, it is assumed it belongs to the *Forests Land remaining Forest Land* category by default. The classification of forest land in each of these subcategories does affect the estimation of the GHG emissions and removals, for the 2006 IPCC Guidelines prescribe a different accounting methodology for each of them.

Apart from that main subdivision, the Earth's forest land is commonly divided into several types according to site factors, plantation types, development stage, or management practices in order to better assign forest parameters, such as growth rates, when estimating GHG emissions, and thus reduce uncertainty. Although practitioners are always encouraged to push further this stratification (and report it transparently), in many cases the lack of data at higher levels of refinement poses an obstacle to do this.

In general, there are two main methods used to estimate GHG emissions and removals from the 5 relevant carbon pools (above ground biomass, below ground biomass, dead organic matter, litter, soil organic matter) in forest land: the *Gain-Loss* and the *Stock-Difference* method. Each has its strengths and weaknesses and may be more or less suitable depending on the tier approach used, the pool, the type of forest, etc. Besides, some carbon pool stock changes are more difficult to assess than others, imply higher degrees of uncertainty, and require higher tier approaches (e.g., dead organic matter) and thus larger amounts of data. How these choices and requirements may impact a GHG inventory, and affects its uncertainty, may depend on the relevance of the different pools in the area covered by the inventory.

Finally, in addition to the CO_2 emissions and removals from the 5 main pools, there also might be non-CO_2 emissions, which are mainly due to managed and uncontrolled fires. These will also produce GHG emissions that, unlike in other land types, will have to be considered for they occur at a much higher rates than CO_2 uptake.

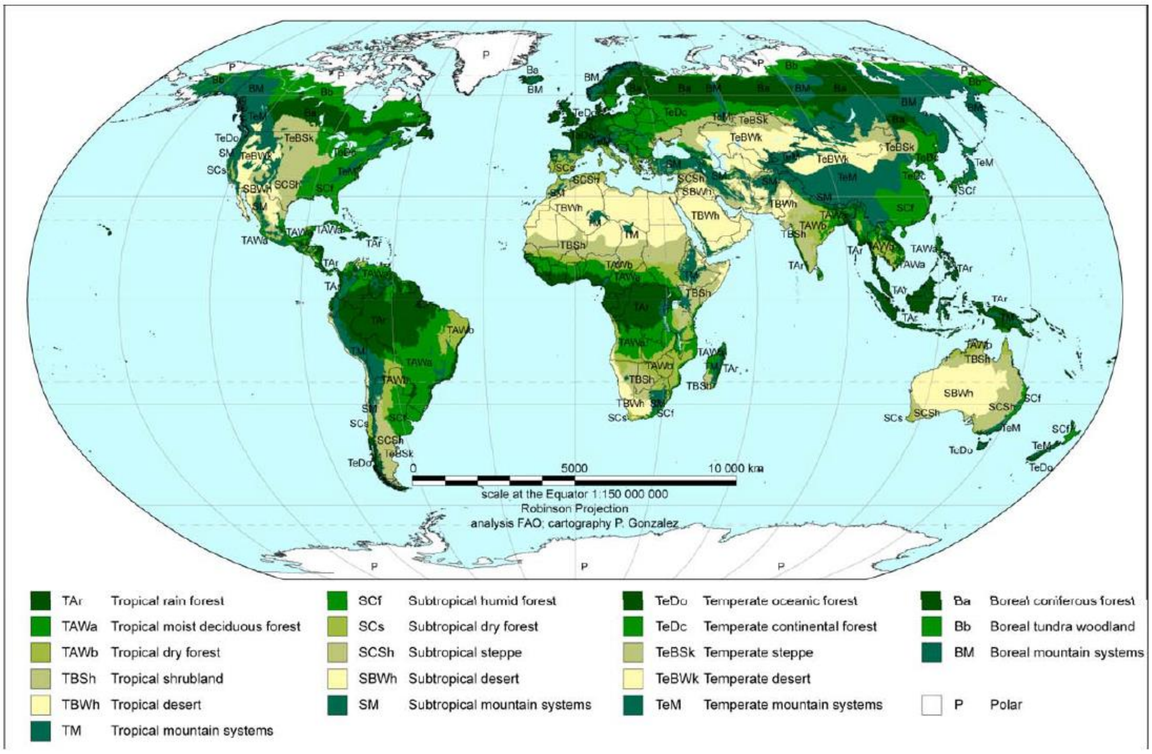

Figure 4.4.Forest cover types 2006 IPCC Guidelines Vol. 4, Chapter 4 (IPCC, 2006a)

4.3.2 Cropland

Cropland may extend from arable land for all annual and perennial crops to certain kinds of agroforestry, as long as the vegetation structure does not fit into the Forest Land category. As a consequence of the wide diversity of crop types, climate variables, and management practices, many different carbon stock regimes and dynamics can be found within croplands, from short-term carbon storage in annual crops harvested every year (e.g., cereals), to long-term carbon storage in perennial crops (e.g., vineyards). This also has repercussions in GHG accounting. For instance, the annual change in biomass carbon stock for annual crops is considered to be equal to the sum of the harvested, lost, and dead biomass.

Like Forest Land, Cropland may also be divided into two main subtypes: *Cropland remaining Cropland* and *Land Converted to Cropland*. Regardless the subtype, there are 5 main carbon pools in Croplands for which GHG emissions and removals estimation methodology is provided:

- Above ground biomass
- Below ground biomass
- Dead wood
- Litter
- Soils

The methodology to be used may greatly change from one pool to the next, and in some cases several different methods can be used for the same pool. It will be up to the practitioner to decide which would be the most appropriate for the specific case. For instance, the carbon changes in biomass (and in other pools too) can be calculated either using the annual rates of biomass gain and loss or estimating the carbon stock changes at two points in time. However, whilst the former can be used with any Tier approach, the latter can only be used with Tier 2 or 3.

In addition to this, unlike in Forest land where all carbon pools are relevant regardless of the specific pieces of land being assessed, in Cropland, the relevance of the different carbon pools depends on diverse factors. Thus, for instance, dead wood and litter are almost non-existent for most crop types, (with the exception of agroforestry systems), such that under Tier 1 approaches it is assumed that there is none. On the other hand, given the diversity of management practices, soil carbon is quite relevant and may vary a lot across climate regions, crop types, etc.

As for the non-CO_2 emissions, they are normally the result of burning agriculture residues. In Cropland, unlike in Forest land, CO_2 emissions are not accounted in this event for it is assumed that they will be reabsorbed within short period of time due to crops low carbon content and high growth rates.

4.3.3 Grassland

Although grazing is in general the main use for Grassland, the differences in its management intensity can be large, ranging from extensive pastoralism on rangelands to the intensive management typical of pastures and meadows. Another characteristic specific to Grassland is the predominance of below-ground biomass and soil organic matter over the other carbon pools. However, the particular carbon stocks in each pool depend greatly on the management practices, the interannual climate variability (which influences in turn the management decisions), and natural disturbances, such as fires. As a matter of fact, the latter occur in Grasslands more often than in any other land type and not always with a negative effect; fire may for instance also provide some benefits by preventing the expansion of woody species.

Similar to other land types, there are different GHG accounting methods (e.g., gain-loss, stock change) and the use of one or another Tier approach implies accepting some assumptions. For instance, according to Tier 1, if there is no change in management intensity, the change in grassland biomass (above and below ground) is 0, i.e., carbon absorbed through plant growth is almost completely offset with losses through grazing, decomposition, and fire. However, this assumption becomes quite inaccurate when management intensity varies. Therefore, countries where Grassland is a key source should avoid using Tier 1 approaches for biomass.

As mentioned before, soil carbon is one of Grassland's most relevant carbon pools. Soil carbon is subject to the influence of many factors such as fertilizing, irrigation, grazing intensity, fires, etc. and the estimation of its GHG emissions and removals therefore requires accurate data on Grassland areas, management practices, etc. without which the results may be hampered.

4.3.4 Wetlands

Only managed wetlands (land covered or saturated by water for all or part of the year) are considered, i.e., artificially created wetlands or wetlands where the water table is actively regulated. There are two main subcategories within wetlands: peatlands and flooded lands. It should be noted that wetlands may easily pass by means of management activities to other land types such as grassland or cropland. Non-managed wetland GHG emissions and removals will not be accounted for.

Unlike other land types, due to the complexity of its carbon dynamics and the continuous changes they are subject to in some cases, wetland GHG accounting methodologies are in general still in the research phase and no specific methodology has been developed for some management types (e.g., aquaculture ponds, industrial effluent ponds, etc.). This gap in methodology development may have a great impact in the GHG accounting of those countries where these activities are more relevant.

Wetlands differentiate from other land types in the role anaerobic decomposition (limited oxygen availability) plays, which, unlike aerobic decomposition, leads mostly to CH_4 emissions instead of CO_2 emissions, making wetlands the single largest natural source of CH_4. Besides, either through aerobic or anaerobic decomposition, in most wetlands, up to 90% of the carbon uptakes are released to the atmosphere by decay. For these reasons, the creation of wetlands or the conversion of wetlands to other land types (where CO_2 emissions are prevalent) may produce great changes in GHG emissions and removals.

The GHG accounting methodologies applied so far differ greatly between peatland and flooded lands due to their very different natures. Peatlands are among the Earth's largest terrestrial carbon reservoirs and their management is therefore a relevant issue for climate change. They have their origin in the generation of dead organic matter at a pace higher than the rate of decay and also show a low carbon absorption rate compared to croplands. Another important aspect is that the emissions produced when burning peatland for energy production off-site (ca. half of all peatland production is dedicated to this goal) are not reported as part of the AFOLU sector but within the energy sector. As for flooded lands, unlike peatlands, they do not have yet their own GHG accounting methodologies and depend on those from other land types.

4.3.5 Other land

Defined as the land that does not fall within any of the other land categories, which means this category comprehends a wide range of land types from bare soil to rock and ice. It is not usually a key category, and in most cases, it is not under management and therefore its emissions are not subject to GHG emissions accounting. For this reason, guidance is only provided for *Land converted to Other land,* when changes in carbon stocks and non-CO_2 emissions may occur (e.g., deforestation).

The methodologies applied to estimate GHG emissions and removals when land is converted to Other Land are not very different from the ones used for Cropland or Grassland. The main differences are the assumptions made to reflect characteristics specific to Other Land. For instance, when calculating the differences in biomass stock before and after the land conversion it is assumed the biomass stock after the conversion will be 0. The same applies to dead organic matter which, under Tier 1 approaches, is considered to be 0 also for other land types. As for the carbon held in the soil, it is assumed this will be released until it reaches 0. If this does not happen, it is very likely the land should be classified under a different land type.

4.3.6 Livestock

Livestock distinguishes itself from the other AFOLU subsectors in several aspects. It is for instance a GHG source (no removals) with two major components: *enteric fermentation* (CH_4) and *manure management* (CH_4 and N_2O). Net CO_2 emissions from livestock are assumed to be 0, since the CO_2 absorbed by the plants eaten by the livestock is returned to the atmosphere as respired CO_2.

Only the emissions from animals under domestic management are considered for the compilation of the GHG inventory.

The main initial step for the estimation of Livestock GHG emissions is the definition of livestock categories and their corresponding populations. For this first step, different Tier approaches may be used, with the higher ones also including more detailed information on feed intake and feed digestibility coefficients, among others.

The CH_4 emissions from enteric fermentation (i.e., originating from animals' digestive systems) are greatly affected by numerous factors, ranging from age and weight to feed intake, quantity and quality. This is only relevant for ruminants, since non-ruminant livestock like swine produce much less CH_4 during digestion. Therefore, if in a given country ruminants are not a key category, a Tier 1 approach can be used, and the efforts required to gather all the data for these calculations can be saved.

The emissions produced through manure treatment and storage do not depend on the livestock types and are heavily influenced by the amount of manure and the portion of the same that decomposes anaerobically (resulting in CH_4). If the decomposition occurs under aerobic conditions (e.g., on pasture) the amount of CH_4 released will be lower. On the other hand, N_2O emissions from manure occur through nitrification (aerobic) and denitrification (anaerobic) processes or through volatile losses provided the manure contains nitrogen. N_2O emissions also influence the amount of nitrogen remaining in the manure and therefore its utility as fertilizer. In both cases GHG emissions are greatly influenced by the management practices being implemented.

Finally, it must be mentioned that the emissions arising from the burning of manure will not be accounted under the AFOLU section emissions but under those of the Energy or Waste (if there is no energy recovery) sectors.

4.3.7 N_2O and CO_2

This sector covers N_2O emissions from managed soils (regardless the land type), including indirect N_2O emissions from additions of N to land (deposition and leaching) and CO_2 emissions resulting from the addition of fertilizers.

Under certain circumstances and provided the presence of nitrogen, N_2O can be naturally produced in soils through nitrification (aerobic) and denitrification (anaerobic) processes. Through different practices (e.g., fertilizers, manure deposition, crop residues, land-use change, etc.) the soil nitrogen content can be modified, and the above-mentioned processes artificially triggered. The emissions may be direct (resulting from the addition of nitrogen to the soil) or indirect (through volatilization of NH_3 and other nitrogenous compounds from soils or fossil fuel combustion). As for CO_2 emissions from managed soils, there are two main sources: liming and urea fertilization.

4.3.8 Harvested Wood Products (HWP)

Currently there are three main approaches for reporting the carbon stored in wood products and none of them are widely preferred over others. The main differences between them relate to the way they allocate the CO_2 from HWP between consuming and producing countries and their focus on either stock changes or atmospheric fluxes. The 2006 IPCC Guidelines focus on the variables (annual stock change, harvested amount, imports and exports) required for some of the approaches and how to gather the required data. It should be noted that the three approaches are mutually exclusive, i.e., they cannot be combined.

Regardless of the approach, the main assumption to estimate HWP emissions is that the amount of woody material in use decays following an equation of first- (more common), second-, third- etc. order. HWP may also be a CO_2 source when burnt, but in that case the emissions will be accounted under the Energy sector, or when deposited in solid waste disposal sites. However, in this case the CO_2 emissions will not be accounted under the Waste sector. CH_4 emissions, regardless of their origin, will always be included in the HWP account.

HWP acts as a carbon reservoir and includes all the material that leaves harvest sites. For how long carbon will be held in HWP and how long it will take for it to decay depends on the use (e.g. fuel wood vs furniture). In some cases, for example when the annual carbon change in HWP stocks is smaller than that of any key category, emissions may be considered insignificant and rounded to 0. Therefore, using Tier 1 approaches to get a first idea of the relevance of the emissions and compare them with those from other categories is a common practice. However, since the emissions estimations may vary depending on which of the three approaches is used, it will be difficult to assess whether HWP is a key category or not and which is its relevance in regard to other categories. This also makes it difficult to choose which Tier approach to use to estimate the emissions.

4.4 GHG inventory limitations relevant to AFOLU

When compiling a GHG emissions inventory there are a number of issues that may affect the end result and end up hampering its usefulness when it comes to accounting for the effects of mitigation actions through them:

- *Methodological level:* The measure must influence a pool or parameter considered by the IPCC methodologies at the tier level applied by the country for it. If the tier level selected is too low the methodology may not be able to capture the effects of the measures (see example below). It is considered that most of the AFOLU mitigation action effects can be captured by using an IPCC Tier 2 methodology which is the one recommended by the IPCC 2006 for all key source categories (Leip, 2017).

Influence of Tiers on inventory results: In 2017, most developing countries still used the Tier 1 approach to calculate enteric CH_4 emissions from ruminant livestock. According to this, emissions are calculated by multiplying animal numbers and default emission factors, which may vary by species and region, but are not influenced by feed quality, productivity improvements, and management practices which could make emission levels decrease. Therefore, GHG inventories will not reflect emission reductions from mitigation actions except if these affect the number of animals (Wilkes *et al.*, 2017).

- *Lack of data:* This is related to the first point since the use of high tier methodologies sometimes requires measuring and research activities (to estimate the right emission factors for instance) that some countries are not in the position to undertake rendering the accountability of some mitigation effects almost impossible. For instance, the availability of information below farm level is reduced and for that reason GHG emissions accounting is usually made only at farm level which allows to be more comprehensive when assessing the effects of mitigation actions but might still miss changes occurring within the farm (Leip, 2017). In general, the effects of mitigation actions targeting features measurable through statistical surveys (e.g. reduction of animal numbers) are more likely to be captured and traced in a national GHG inventory than the effects of those mitigation actions targeting parameters requiring experimental measurements.

- *Indirect effects:* A mitigation action may also have effects beyond the targeted pool or category or beyond the assessed timeframe which shall also be considered.

Indirect land use change (ILUC): There are many activities competing for the use of land, such as agriculture, forestry, or bioenergy, and therefore any action that affects the use or management of a piece of land may unchain further changes in other places. For instance, if crop land is converted into land to grow biofuels crops then, somewhere else, new land might be found to grow food crops, which may lead in turn to deforestation or other land changes. If these further changes of land occur outside the boundaries of the baseline set to assess the effects of the initial land change, they will not be taken into consideration and can therefore be considered as a leakage.

Regarding the *indirect effects*, as was previously mentioned, the mere setting up of a reference scenario or baseline against which the GHG emissions changes can be measured may condition the whole assessment. Apart from the bottom-up and top-down approaches introduced in 4.1, depending on the ultimate assessment goal, baselines may also differ from each other in a number of other features. For instance, the baseline's spatial and temporal boundaries, i.e., the geographical area and GHG sources and sinks the baseline comprehends, and the period of time the baseline's projection is valid for. These features are key to comprehending the indirect effects of a measure or render the baseline completely useless if chosen wrongly.

If the boundaries of a baseline set to assess the effects of a certain mitigation action include just some of the GHG sources and sinks within a country or all the sources and sinks but only within a given region, the effects resulting from that action occurring in nearby regions or in other GHG sources and sinks will not be assessed. These impacts occurring outside the boundaries of the baseline are referred as *leakages* and can be avoided, to some extent at least, by expanding the baseline boundaries.

Challenges may also arise from baselines' temporal boundaries. If not chosen carefully, they may leave out some of the more lasting effects of the assessed mitigation action, i.e., those with a longer permanence, or those occurring later in time (see example below). For this reason, it is important to take into account the *permanence* of the effects of the actions to be assessed, a concept mainly used in relation with the AFOLU sectors and referring to the longevity and variability of carbon pools, i.e., how long the captured carbon remains in the soil or vegetation category.

Example for permanence in reforestation: In a reforestation project, tree growth leads to an initial increase in CO_2 removal from the atmosphere. The so captured carbon will be stored in the biomass of the trees. So far, the action would pose a net removal of GHG from the atmosphere. However, if, after a given period of time, these trees die, are harvested to build furniture or produce pellets, the mitigation effects of the initial actions will be, at least partially, reversed, since part of the initially stored carbon will be released into the atmosphere again when the pellets are burnt, i.e., the carbon is not permanently stored in the pellets. In such a case, the estimated mitigation effects of the project would depend on the temporal boundary of the baseline set to assess the effects of the reforestation project. Thus, if this is set before the harvesting, the mitigation effects of the project would appear much larger than they would be if it were set after the harvesting.

There are some strategies to avoid non-permanence, i.e., the *reversibility* of the effects of mitigation actions and measures. For instance, in the previous example, the unforeseen release of the captured carbon from premature death can be mitigated by creating buffer pools to offset unforeseen losses in carbon stocks. However, the most efficient way to tackle reversibility is by pursuing policies that place greater value on permanent over temporary carbon sequestration and strive to produce a transformational change in human activities, such as the implementation of sustainable management practices(OECD, 2019).

In the end, as it was said before, all these issues make it difficult to prove the benefits of a given mitigation action or policy, i.e., its *additionality*, understood as the property of those actions without which the mitigation effects most likely would have not taken place. However, even though GHG inventories may not be able to reflect the additionality of some measures, they can be shown through the comparison of baselines and mitigation scenarios. For instance, if nothing changes, in the future the growing human population is expected to require an increase in land dedicated to the production of food and fodder which may, in turn, lead to the depletion of carbon stocks through deforestation and thus increase AFOLU GHG emissions. This would be the Business-as-Usual (BAU) scenario or baseline. But, if through the introduction of new managing practices or the development of new technologies, productivity is increased and the main driver for land conversion is cancelled out, it might become possible to keep the AFOLU emissions levels approximately as they are now. This will not be reflected in the inventories but will be clearly seen when comparing the actual GHG emissions evolution with the BAU baseline. In this way the additionality of the measures implemented would be proven.

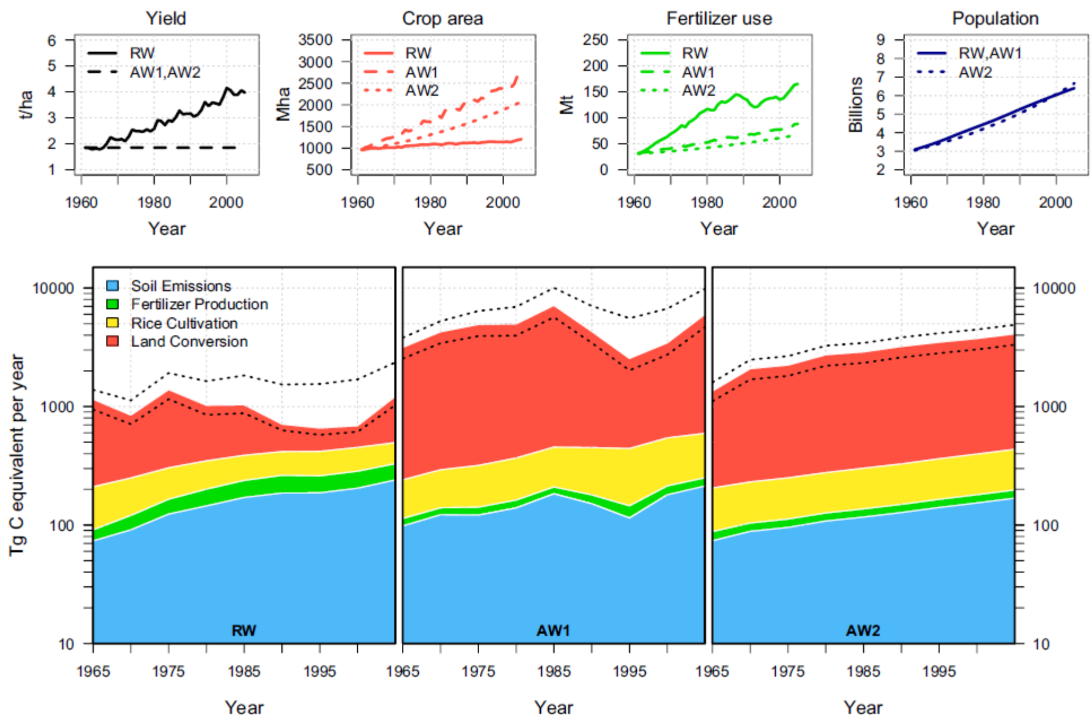

Figure 4.5. World Agriculture GHG emissions 1961-2005: Three different scenarios. RW is the agriculture intensification scenario (higher yields, higher application of fertilizers, low land expansion) whilst AW1 and AW2 are two possible alternative worlds. In AW1 agriculture technology and farm practices as in 1961. In AW2 the required innovations are introduced to increase productivity only enough to maintain 1961 living standards - (Burney *et al.*, 2010)

Box 4.3.Costa Rica Knowledge Management System for managing forest and ecosystem services.

Costa Rica has set up a solid political framework that recognizes the relevance of climate change mitigation and adaptation measures and promotes a sustainable development model. With this approach, Costa Rica has achieved widely acknowledged successes in forest conservation and sustainable management which, over the years, has led to the reforestation of large areas of the country. These efforts come as a recognition of forests' key roles in climate change adaptation and mitigation (BID-MINAE-SINAC-DCC, 2015).

However, the decision-making process regarding mitigation and adaptation strategies requires more and better information (MIDEPLAN, 2014). In particular, a 2012 Technology Needs Assessment identified a lack of instruments to facilitate access to information in relation to the management of forests and associated ecosystem services. The envisioned instrument would be able to gather and disseminate the large amounts of related technical and scientific information available, analyse it, and provide information that facilitates the design of adaptation and mitigation strategies and thus the sustainable management of forests.

In 2017 Costa Rica submitted a request to the Climate Technology Centre & Network (CTCN) to obtain assistance with the implementation of a knowledge management system (KMS) for managing tropical forests and ecosystem services. This KMS was conceived as an instrument to improve strategy design and decision-making in relation to management of forests ecosystems. The KMS includes a data and information management system for gathering and managing geospatial information on tropical forests, administrative and financial databases, and a set of IT tools that allow to calculate and disseminate indicators relevant to the sustainable management of forests and their ecosystem services and thereby support evidence-based decision-making.

The Ministry of Environment and Energy, the National Forest Finance Fund, and the Climate Change Department, together with the Foundation for the Development of the Central Volcanic Cordillera (FUNDACOR) and local stakeholders where in charge of providing the required inputs and general support to the CTCN during the project implementation. They are also the bodies responsible for the monitoring and evaluation of the impacts of the projects once it had been concluded.

It is expected that the implementation of this KMS will improve the country's capacity to design mitigation and adaptation strategies for the management of forests and ecosystems services. The KMS will also increase the adaptive capacity in relation to the expected climate change impact on forests. As for the specific actors profiting from the KMS, it is expected that government (national, subnational, and local) and private sector, as well as planners and local communities will benefit from the information provided on forests and ecosystems services and support policy-making related to land use, agriculture, and biodiversity.

Source: (CTCN, 2017)

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Annexes

Annex 1: Description of tools relevant for mitigation in the AFOLU sector
Annex 2: Data requirements per sink/source category according to the Tier method applied.

Annex 1 Description of tools relevant for mitigation in the AFOLU sector

Type	Developers	Name	Description	Link
Tool	IPCC	IPCC Inventory Software	The IPCC Inventory Software implements the simplest Tier 1 methods for all sectors and Tier 2 methods for most categories under Energy, IPPU and Waste Sectors as well as Agriculture categories under AFOLU Sector in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (please see Tier2_coverage.xlsx). Making it compatible with the Tier 2 methods for the Land component of the AFOLU sector is still an ongoing work.	IPCC Inventory Software
Online tool	World Agroforestry (ICRAF), CGIAR Research Program on Agriculture, Climate Change and Environment (CCAFS), Partnerships for Scaling Climate-Smart Agriculture (P4S-CSA)	Evidence for Resilient Agriculture (ERA)	It is a dynamic dataset and website that provides data and tools to assess the performance of different agriculture technologies in diverse contexts.	ERA
Model	FAO	Global Livestock Environmental Assessment Model (GLEAM)	It is a spatially explicit life cycle assessment model for the livestock sector. Using input data on herd, feed, and manure management, it calculates GHG emissions for livestock supply chains (6 species) using an IPCC Tier 2 methodology. Some of its outputs are: Livestock numbers and distribution, production and management data on manure, animal feed rations (composition and quality, livestock commodities production, greenhouse gas emissions from each stage of production and emission intensities by commodity.	GLEAM
Tool	Metro Manila, Philippines: International Rice Research Institute (IRRI)	Source-selective and Emission-adjusted greenhouse gas CalculaTOR for cropland (SECTOR)	SECTOR is a Greenhouse Gas Calculator for cropland based on the IPCC Tier 2 approach for rice and other crops. The tool is currently available as an EXCEL file and requires inputs on crop area, yield, and management. SECTOR was developed in response to increasing interest in mitigation research on cropland, particularly rice production. It is flexible in terms of entering emission factors, easy data transfer from crop statistics for entering activity data and specifications of GHG management scenarios. Several example templates are available for free download for users to test the tool in EXCEL.	SECTOR
Tool database	NDC Partnership	NDC Toolbox Navigator	The NDC Toolbox Navigator is a searchable database of tools, guidance, and advisory support to help countries implement their NDCs (Nationally determined contributions). The database includes key analytical tools and guidance documents, experience profiles, links to other knowledge platforms, and sources of advisory support that are relevant to NDC planning and implementation for both mitigation and adaptation.	NDC Toolbox Navigator
Online tool	FAO	Emissions overview Tool	The Emissions Overview tool report gives emissions and trends in the AFOLU sector, subdivided by source categories, for one or more user-specified countries. It also contextualizes emissions within the regions, continents and globally. It is based on the FAOSTAT emissions database. It aims to support countries in the preparation of NAMAs and NDCs.	Emissions Overview Tool

Online tool	FAO	Quality Assurance/ Quality Control (QA/QC) and Verification	The tool allows users to compare national GHG inventory data for the AFOLU sector reported to the UNFCCC with data from the FAOSTAT Emissions database. The tool can help countries improve their capacity to report the AFOLU sector in their National GHG Inventory.	Quality Assurance/ Quality Control (QA/QC) and Verification
Guidance/Methodology	CDM	Clean Development Mechanism (CDM) methodologies for agriculture	Repository of methodologies intended for monitoring of CDM projects.	Clean Development Mechanism (CDM) methodologies for agriculture
Guidance/Methodology	Initiative for Climate Action Transparency (ICAT)	ICAT Forest Methodology	The Forest Methodology helps policymakers assess the impacts of forest policies to ensure that they are effective in mitigating GHG emissions, and helping countries meet their sectoral targets and national commitments. The document provides methodological guidance for assessing the GHG impacts of forest policies that increase carbon sequestration and/or reduce GHG emissions from afforestation and/or reforestation, sustainable forest management and avoided deforestation and/or degradation.	ICAT Forest Methodology
Guidance/Methodology	Initiative for Climate Action Transparency (ICAT)	ICAT Agriculture Guidance	The Agriculture Guidance supports the assessment of the GHG impacts of agricultural policies and actions. This guidance fills a gap in currently available guidance, which includes project-level agricultural GHG accounting, but does not include GHG accounting at the agricultural policy level. The Agriculture Guidance leverages existing methods and tools to provide general principles, concepts and a method for estimating GHG impacts	ICAT Agriculture Guidance
Tool	FAO	Ex-Ante Carbon-balance Tool (EX-ACT)	It accounts for GHG emissions covering the entire AFOLU sector, including agricultural inputs, energy, infrastructure, management of organic soils, coastal wetlands, fisheries and aquaculture. Part of the Mitigation of Climate Change in Agriculture (MICCA).	EX-ACT
Tool	FAO	Biodiversity Integrated Assessment and Computation Tool (B-INTACT)	It makes use of various geo-referenced maps and tools to increase accuracy and account for the ecological value and biodiversity sensitivity of project sites. Mitigation of Climate Change in Agriculture (MICCA)	B-INTACT
Tool	FAO	EX-Ante Carbon-balance Tool for value chains (EX-ACT VC)	It supports policy makers in identifying off-farm sources of GHG emissions and farm-to-retail socio-economic benefits when designing projects and policies for low carbon value chains. Mitigation of Climate Change in Agriculture (MICCA)	EX-ACT VC
Model	International Institute for Applied Systems Analysis (IIASA)	Global Biosphere Management Model (GLOBIOM)	It is a partial-equilibrium model representing various land use-based activities, including agriculture, forestry and bioenergy sectors. It is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. GLOBIOM is used to analyse the competition for land use between agriculture, forestry, and bioenergy, which are the mainland-based production sectors. As such, the model can provide scientists and policymakers with the means to assess, on a global basis, the rational production of food, forest fibre, and bioenergy, all of which contribute to human welfare.	GLOBIOM

Online tool	Agriculture and Food Development Authority (Teagasc)	Carbon Navigator	The Carbon Navigator has been developed to support the objective of reducing the carbon intensity of the dairy and beef sectors of Irish agriculture. The system is designed as a knowledge transfer (KT) tool aimed at supporting the realisation at farm level of the mitigation potential from the implementation of sustainable farm practices by estimating the percentage reduction in farm GHG emissions resulting from the implementation of sustainable farm practices. This way the Carbon Navigator may help to achieve the adoption of emission-reducing technologies and practices at farm level.	Carbon Navigator
Tool	Wageningen University & Research	Kringloopwijzer	It is an online management tool developed by the dairy industry that tracks the nutrients entering and leaving farms and can help monitor farm level N_2O emissions. It aims to improve farm nutrient-use efficiency by providing indicators such as nitrogen and phosphate levels, nitrogen and phosphate surpluses, mineral use and NH_3 emissions. Farmers can then compare their environmental performance with legal standards and with that of other farms.	Kringloopwijzer
Online tool	Centre National Interprofessionnel de l'Économie Laitière	CAP'2ER	CAP'2ER provides GHG emissions, energy consumption, biodiversity conservation, water and air quality, and carbon storage indicators at the farm level	CAP'2ER
Model	Agriculture and Agri-Food Canada	Holos	Holos is a whole-farm model and software program that estimates greenhouse gas (GHG) emissions based on information entered for individual farms. The main purpose of Holos is to test possible ways of reducing GHG emissions from farms and is available at no cost to users. Users can select scenarios and farm management practices that best describe their operation and then adjust these practices to see the effect on emissions. Examples of these adjustments include changing livestock feed, reducing tillage or including perennial forages in rotation.	Holos
Online tool	Brazilian Roundtable on Sustainable Livestock (GTPS)	GIPS	It is an online assessment tool that enables users to test their own sustainability performance as well as that of members of their value chain. It includes sustainability indicators related to GHG emissions intensity of beef production (including emissions from land use conversion), soil conservation, water consumption, energy efficiency, waste treatment, air quality, deforestation, and compliance with the Forest Code's requirements.	GIPS
Model	National Institute of Environmental Studies, Japan	AIM (Asia Pacific Integrated Model)	The AIM (Asia Pacific Integrated Model) is an integrated assessment model made up of three modules: the greenhouse gas emission, the global climate change model and the climate change impact model. The third of these makes the model relevant to assessing the response measures. However, the model also contains a very detailed technology selection module to evaluate the effect of introducing advanced technologies in the Asia-Pacific region. The AIM model is particularly useful when analysing the development and diffusion of new 'greener' technologies in the Asia-Pacific region.	AIM
Model	US Environmental Protection Agency	ASF	ASF is an integrated assessment model, which provides a framework for developing scenarios of future emissions based on consistent demographic, economic, and technological assumptions. Its strength is in its links between the use of biofuels, land use, technological development and GHG policy. It is therefore an appropriate tool for evaluating the land-use impacts of response measures. The ASF model is used for analysing the development of clean technology in areas that are not related to energy	

			generation, such as land use. These areas are often less well covered by other models, making it an important tool.	
Model	OECD Environmental Directorate	ENV-Linkeages	ENV-Linkages is the successor to the OECD GREEN model and is now hosted by the OECD Environment Directorate. The modelling work based on ENV-Linkages aims to assist governments in identifying least-cost policies or policy mixes on a range of environmental issues, including mitigation of climate change, phasing out fossil fuel subsidies and other green growth policies, such as environmental tax reform.	ENV-Linkeages
Model	Netherlands Environmental Assessment Agency	FAIR	The FAIR model is an interactive, decision-support tool to analyse the environmental implications and economic costs of climate mitigation regimes. The model links long-term climate targets and global reduction objectives with regional emissions allowances and abatement costs, so is particularly useful for looking at some of the more detailed Kyoto mechanisms.	FAIR
Model	Potsdam Institute of Climate Impact Research	ICLIPS	ICLIPS seeks to provide Integrated Assessment of Climate Protection Strategies to support the decision-making community. The model assesses the social and economic consequences of climate-change policies. It consists of three modules looking at climate effects, the impacts of these effects and the socio-economic outcomes. ICLIPS is particularly useful in investigating methods of economic diversification in various world regions, as well as the assessment of the socio-economic impacts of climate change mitigation policies. The basis for the model is the two-way linkages between society and the climate, making it an appropriate tool for assessing the economic, social and environmental impacts of response measures.	ICLIPS

Model	Netherlands Environmental Assessment Agency	IMAGE	IMAGE is a multi-disciplinary, integrated system of models designed to simulate the dynamics of the global society-biosphere-atmosphere system. Its particular strength is that it can assess the social and economic impacts of policies aimed at reducing emissions from land-use change. The IMAGE model is relevant in assessing the socio-economic impacts of the climate change mitigation policies, in particular the impacts on the agricultural economy, land use and trade, as well as energy demand and supply. The model can forecast up to 2100 and has a spatial scale grid of 0.5 x 0.5 degrees latitude-longitude for climate, land-use and land-cover processes, and region-level split for socio-economic indicators. The model is mainly used to: investigate linkages and feedbacks in the global society-biosphere-atmosphere system; assess consequences of global policies; analyse relative effectiveness of various policy options addressing global change.	IMAGE
Model	Joint Global Change Research Institute (PNNL)	GCAM	GCAM is an integrated assessment model that focuses on the world's energy and agriculture systems and includes numerous energy supply technologies. The model is mainly used for: +estimating the impacts of technologies and policies related to GHG +emissions in a national and global context; +evaluating different technologies, including carbon sequestration; +land-use/ agriculture modelling; +basic climate change modelling. GCAM is relevant to analyse the development of new environmentally-friendly technologies, as well as evaluating the performance of existing conventional ones. The model can also be useful when looking at the diffusion of technology across global regions.	GCAM

Model	Joint Global Change Research Institute (PNNL)	Second Generation Model (SGM)	SGM is a computable general equilibrium model with emphasis on demographics, resources, agriculture, energy supply and transformation, energy intense industries, household consumption, and government expenditure. The model is used to project energy consumption and greenhouse gas emissions but its main relevance is its use in evaluating the economic impacts of climate change policies and the use of technologies for emissions mitigation. The SGM model is relevant in assessing the socio-economic impacts of climate change mitigation policies, with a specific focus on resources, agriculture and energy-intensive industries.	SGM

Annex 2: Data requirements per sink/source category.

GHG relevant Carbon Sources and Sinks		Biomass pools (CO_2)			
		All LU categories	Land remaining in LU category	Land converted to another LU category: Conversion year	Land converted to another LU category: After conversion year
Data	Tier 1	Area affected divided by land use categories and IPCC climate and vegetation zones and crop types	Forest increment and loss (only above ground biomass)	Pre- and post-default carbon stocks.	Forest increment and losses due to harvesting, fires, and other disturbances (only above ground biomass)
	Tier 2	Area affected divided by land use categories and country-specific forest/vegetation/crop types	Forest and any other perennial biomass increment and losses	Country-specific pre- and post-default carbon stocks.	Forest and any other perennial biomass increment and losses due to harvesting, fires, and other disturbances.

GHG relevant Carbon Sources and Sinks		SOM Mineral Soils CO_2 & N_2O			SOM Organic Soils (CO_2, CH_4, N_2O)
		All LU categories	Land remaining in LU category	Land converted to another LU category	
Data	Tier 1	Area corresponding to each SOM type divided by default soil types, management systems, and carbon inputs.	SOM ignored	•Default SOC values. •Default SOC factors per LU, management systems and pre-and post-conversion carbon inputs. •Default nitrogen fraction in SOM.	Area corresponding to each SOM type divided by: •Peat nutrient status and drainage depth. •Default CO_2, CH_4 and N_2O EF in drained/rewetted land.
	Tier 2	Area corresponding to each SOM type divided by country-specific soil types, management systems, and carbon inputs.	SOM changes.	•Country-specific SOC values. •Country-specific SOC factors per LU, management systems and pre-and post-conversion carbon inputs. •Country-specific nitrogen fraction in SOM.	Area corresponding to each SOM type divided by: •Country-specific variables. •Country-specific CO_2, CH_4 and N_2O EF in drained/rewetted land.

GHG relevant Carbon Sources and Sinks		Manure management (CH_4, N_2O)	Enteric fermentation (CH_4)	Inorganic and organic fertilizers (N_2O & CO_2 limited to urea and other carbonate fertilizers)
Data	Tier 1	•Average number of heads of each livestock species divided by main categories, manure management system (MMS) and climate zones. •Average annual temperature. •Default nitrogen excretion rate per livestock species. •Animal average mass per livestock category. •Default N_2O EF per MMS. •Default fraction of volatising managed manure nitrogen per livestock category. •Default N_2O EF from atmospheric N deposition.	•Average number of heads of each livestock species divided per main categories and climate zones. •Default enteric fermentation CH_4 EF.	•Quantities of fertilizer applied divided by type and culture. •Default fertilizer applied nitrogen content. •Default volatilized nitrogen fraction. •Default leached nitrogen fraction. •Default N_20 direct and indirect N_2O emissions EF. •Other ignored carbonate fertilizers carbon content. •Default urea CO_2 EF.
	Tier 2	•Average number of heads of each livestock species divided by enhanced main categories, manure management system (MMS) and climate zones. •Fraction of manure per MMS [2]. •MCF [1] per management system and climate zone. •Fraction of nitrogen annual intake retained. •Fraction of crude protein. •N_2O EF by country and MMS. •Fraction of nitrogen from managed manure that volatises per country and livestock category. •N_2O EF from nitrogen atmospheric deposition by country. •Max. CH4 producing potential [3] per livestock category. •Livestock gross energy intake (GE) •Feed digestibility (DE) [4]. •Urinary energy (UE) [5] •Manure ash content. • Fraction of annual nitrogen intake retained by livestock. •Fraction crude protein. •Direct N_2O EF from MM by country. •Fraction of volatising manure managed nitrogen per livestock category and by country. •N_2O EF from atmospheric nitrogen deposition by country. •Fraction of leaching (into soil) managed manure nitrogen per livestock category. •N_20 EF from leaching (into soil) nitrogen.	•Average number of heads of each livestock species divided per enhanced main categories, management system and climate zones. •MCF [1]. •Gross energy/feed intake (GE).	•Quantities fertilizer applied divided by type, climate and cultures. •Country-specific fertilizer applied nitrogen content. •Country-specific fertilizer volatilized nitrogen content fraction incl. further divisions. •Country specific fertilizer leached nitrogen content fraction incl. further divisions. •Country-specific direct and indirect N_20 emissions EF incl. further divisions. •Other carbonate fertilizer carbon content. •Country-specific carbonate fertilizers CO_2 EF incl. further divisions.

GHG relevant Carbon Sources and Sinks		Litter and Dead Wood (DOM) CO_2				Harvested Wood Products [13] (CO_2)
		All LU categories	Land remaining in LU category	Land converted to another LU category		
				Conversion year	After conversion year	
Data	Tier 1	Area corresponding to each DOM type.	DOM ignored	Pre- and post-default carbon stocks.	DOM net accumulation rate	•Quantity produced with domestic wood divided in paper and solid wood. •Default paper and solid wood half-lives. •Default paper and solid wood carbon content.
	Tier 2		DOM variations	Country-specific pre- and post-carbon stocks variations	DOM variations	Quantity produced with domestic wood divided according to country-specific categories. •Country-specific half-lives for each category. •Country-specific carbon content for each category.

GHG relevant Carbon Sources and Sinks		Biomass/peat burning (CO_2, CH_4, N_2O)		Liming (CO_2)	Energy (CO_2, CH_4, N_2O)[6]	
Data	Tier 1	Area affected divided by biomass and fire type (wildfires, slash and burning or prescribed fire e.g. crop residues burning, savannah burning).	•Default fuel quantity per hectare fuel quantity, divided by peat and aboveground biomass + DOM. •Default CO_2 [11], CH_4, N_2O [12] EF •Default combustion factors.	•Quantities of lime and dolomite applied. •Default carbon fractions. •Default EF.	Energy by source (fuel and process)	•Default fossil fuels carbon content. •Default CO_2, CH_4, N_2O EF per energy source (fuel and process)
	Tier 2		•Country-specific fuel quantity per hectare, divided by peat and aboveground biomass + DOM. •Country-specific CO_2 [11], CH_4, N_2O EF •Country-specific. combustion factors.	•Quantities of lime, dolomite and other country-specific inorganic and OA. •Country-specific fractions. •Country-specific EF.		•Country-specific fossil fuels carbon content. •Country-specific CO_2, CH_4, N_2O EF per energy source (fuel and process)

GHG relevant Carbon Sources and Sinks		Rice paddy management (CO_2, CH_4, N_2O)	Crop/grass biomass residues (N_2O)
Data	Tier 1	•Area under rice cultivation by water regime, status (pre-cultivation or cultivated), type and amount of organic amendments (OA [7]) applied. •Default EF for permanent flooded fields without OM. •Default scaling factor [9] by water regime before and during cultivation. •OM default scaling factor.	•Areas where residues were left on the field, divided by crop/grass type. •Quantity of crop/grass harvested dry matter. •Default above-ground residues to crop/grass harvested dry matter residues ratio. •Default below-ground residues to crop/grass dry matter ratio. •Default above-ground residues nitrogen content per unit to crop/grass dry matter ratio. •Default below-ground residues nitrogen content per unit to crop/grass dry matter ratio. •Default leached nitrogen fraction. •Default $N_2$0 direct and indirect emissions EFs.
	Tier 2	•Area under rice cultivation by water regime, status (pre-cultivation or cultivated), type and amount of OA applied, soil type and cultivar [8]. •Country-specific EF for permanent flooded fields without OA. •Country-specific scaling factor by water regime before and during cultivation. •Country-specific scaling factor by OA. •Country-specific scaling factor by soil type. •Country-specific scaling factor by cultivar.	•Areas where residues were left on the field divided by crop/grass type and by any other variable according to which country-specific residues mass, nitrogen content and EF may be divided. •Quantity of crop/grass harvested dry matter. •Country-specific above-ground residues to harvested grass/crop dry matter ratio including all further divisions. •Country-specific below-ground residues to harvested crop/grass dry matter including all further divisions. •Country-specific above-ground residues nitrogen content per unit to harvested crop/grass dry matter ratio including all further divisions. •Country-specific below-ground residues nitrogen content per unit to harvested crop/grass dry matter ratio including all further divisions. •Country-specific nitrogen fraction leaches including further divisions. •Country-specific direct and indirect N_2O emissions EF including further divisions.

*If no specification is added, default parameter values are IPCC-given values.
[1] CH_4 conversion factor [%], defines the portion of the methane producing potential that is achieved.
[2] describes the portion of each livestock group's manure that is handled by a specific manure management technique
[3] is the maximum amount of methane that can be produced from a given quantity of manure
[4] fraction of the feed digested [%]
[5] fraction of the gross energy intake excreted as urine [%].
[6] to be accounted for in the energy sector.
[7] anything added to the land e.g. compost, sewage sludge, digestate, cover crop residues mixture.
[8] a plant variety that has been produced in cultivation by selective breeding
[9] dimensionless factor used to modify EF depending on the water regime.
[10] only from urea and other carbonate fertilizers.
[11] only for perennial biomass and only if it has not been included yet in biomass or DOM carbon stock losses.
[12] considered insignificant for peat.
[13] carbon stock changes estimated according to the production approach.