Food and Agriculture Organization
of the United Nations

# CLIMATE CHANGE MITIGATION OPTIONS IN AGRIFOOD SYSTEMS

**Summary of the Working Group III contribution**
to the Intergovernmental Panel on Climate Change
Sixth Assessment Report (AR6)

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**FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS**
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# ACKNOWLEDGEMENTS

This report was written by Mohamed Langston Diagne, under the guidance of Akiko Nagano and the overall supervision of Martial Bernoux.

The publication is a focused synthesis of the Sixth Assessment Report (AR6) by Working Group III of the Intergovernmental Panel on Climate Change (IPCC), with the objective to provide useful guidance for stakeholders to collectively transform agrifood systems in the mitigation of climate change.

Central to the development of the report were technical reviews by the following FAO experts: Laure Sophie Schiettecatte, Iordanis Tzamtzis, Mirella Salvatore.

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# FOREWORD

Agrifood systems are a crucial component of the global economy and their sustainability is imperative for the well-being of our planet and its inhabitants. Climate change poses a significant threat to these systems, and action needs to be taken to mitigate its effects.

The assessment reports of IPCC provide policymakers with state of knowledge assessments on climate change, its implications and potential mitigation pathways. The publication of the Working Group III contribution "Climate Change 2022: Mitigation of Climate Change" to the AR6 in April 2022 marked the completion of the IPCC's sixth round of assessments.

Agriculture is one of the most cost-effective and readily available ways to mitigate climate change in the AFOLU (Agriculture, Forestry and other Land Use) sector. Not only it offers significant climate change mitigation potential, but it also promotes food security and increases the resilience of farmers and communities most impacted by climate change. Mitigation options in agrifood systems, such as sustainable intensification in agriculture, shifting diets, less food loss and waste, provide a significant potential for emissions reduction and enhanced removals.

This report places emphasis on the technological solutions available and their feasibility for implementation, offering a clear path for uncovering the full mitigation potential within agrifood systems. However, barriers such as lack of funding, knowledge gaps, and lack of international collaboration may hinder the implementation of mitigation measures. Furthermore, the implementation of mitigation and adaptation measures may also have important implications on marginalized and vulnerable populations and their communities.

It is vital to consider the concerns of rural poverty and food insecurity for the implementation of AFOLU mitigation measure. In order to ensure that mitigation strategies are comprehensive and implemented successfully, it is also important to take into consideration their effect on vulnerable communities, especially considering that behavioural changes in food systems are required for sustainable agriculture to become a reality. FAO is committed to overcoming the challenges associated with agrifood systems and to create an enabling environment for climate change mitigation in this sector, for better production, better nutrition, a better environment, and better life for all, leaving no one behind.

**Zitouni Ould-Dada**

*Deputy Director, Office of Climate Change,*
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# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **AE** | agroecology |
| **AFOLU** | agriculture, forestry and other land use |
| **AR5** | Fifth Assessment Report |
| **AR6** | Sixth Assessment Report |
| **AWD** | alternate wetting and drying |
| **CDR** | carbon dioxide removal |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **FLW** | food loss and waste |
| **GHG** | greenhouse gas |
| **GWP** | global warming potential |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **JIRCAS** | Japan International Research Center for Agriculture Sciences |
| **LULUCF** | land use, land use change and forestry |
| **MAFF** | Japanese Ministry of Agriculture, Forestry and Fisheries |
| **NARO** | National Agriculture and Food Research Organization |
| **NDCs** | nationally determined contributions |
| **OrgF** | organic farming |
| **SRCCL** | special report on climate change and land |
| **SYR** | synthesis report |
| **UN** | United Nations |
| **WGII** | Working Group II |
| **WGIII** | Working Group III |

## CHEMICAL FORMULAE

| | |
|---|---|
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| **-eq** | equivalent |
| $GtCO_2$ | gigatonnes of carbon dioxide |
| $MtCO_2$ | metric tons of carbon dioxide |
| $N_2O$ | nitrous oxide |
| $tCO_2$ | total carbon dioxide |
| **/yr** or $yr^{-1}$ | per year |

# Introduction

## OBJECTIVE AND STRUCTURE OF THE REPORT

The assessment reports of IPCC are important as they provide policymakers with state of knowledge assessments on climate change, its implications and potential mitigation pathways. With the release of the WGIII contribution "Climate change 2022: mitigation of climate change" for the Sixth Assessment Report (AR6) in April 2022, the IPCC has completed its sixth cycle of assessments. The Synthesis Report (SYR), which will integrate the findings of the working groups and special reports released in this assessment cycle, is scheduled to be released on 20 March 2023.[1]

Several chapters in the WGIII report describe mitigation options that are relevant to agrifood systems, but they figure most prominently in Chapter 7 dedicated to the AFOLU sector.[2] The management of AFOLU is strongly linked to other sectors of the economy and is therefore discussed in other chapters of the report, including Chapter 5 on demand, services and social aspects of mitigation, Chapter 6 on energy systems with regard to bioenergy and Chapter 12 on cross-sectoral perspectives. It is worth highlighting that section 4 in Chapter 12 is dedicated to food systems. AFOLU mitigation options also have important links with IPCC WGII on climate change impacts and adaptation.

In Chapter 14, *International cooperation*, FAO is described as one of the United Nations (UN) agencies implementing and supporting climate actions through much needed technical assistance and capacity building. The AFOLU sector has the capacity to provide for large-scale emissions reduction and to also remove carbon dioxide and store carbon at scale. Furthermore, its response options can benefit biodiversity and contribute to climate change adaptation and the securing of livelihoods, food and water, and wood supplies. (IPCC, 2022b)

This summary report aims to provide useful guidance for policymakers, researchers, practitioners and to lead consumers to take action to collectively transform agrifood systems. It summarizes the findings of WGIII (nearly 3 000 pages), focusing on the assessment's conclusions on mitigation options relevant to agrifood systems, highlighting solution technologies and their implementation feasibility.

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1 For further information see: **www.ipcc.ch/2022/09/09/media-advisory-revised-schedule-ar6-synthesis-report**

2 The AFOLU sector is key to climate change mitigation and has great mitigation potentials especially on emissions reduction and removals associated with $CO_2$, $CH_4$, and $N_2O$. This sector covers an important range of ecosystems and plays an important role for food security because it encompasses key sub-sectors like land, agriculture, livestock, sustainable management of forest, etc.

## BOX 1.

### Highlights

- In 2019, 22 percent of total net anthropogenic greenhouse gas (GHG) emissions were produced by the AFOLU sector, i.e. 13 gigatonnes of carbon dioxide equivalent (Gt$CO_2$- eq). About half of these emissions were derived from the agriculture subsector, predominantly methane ($CH_4$) and nitrous oxide ($N_2O$), while the other half were carbon dioxide ($CO_2$) emissions from land use, land-use change and forestry (LULUCF) including the product of deforestation (IPCC, 2022a).

- Emissions of methane in agriculture continue to increase, the main source is enteric fermentation. Similarly, emissions of nitrous oxide are also increasing, mostly dominated by agriculture, due to manure application, nitrogen deposition and nitrogen fertilizer use.

- Mitigation options in agrifood systems* have high potential and can contribute to major emissions reduction and enhanced removals when sustainably implemented. In the AFOLU sector, agriculture accounts for the second most important share in terms of economic mitigation potential after forests and other natural ecosystems, with an emission of 4.1 gigatonnes of carbon dioxide equivalent per year (Gt$CO_2$-eq/yr) from cropland and grassland soil carbon management, agroforestry, biochar use, improved rice cultivation, and livestock and nutrient management.

- Most mitigation options in agrifood systems are available and ready to deploy, and emissions reduction can be unlocked quickly. Sustainable intensification in agriculture, shifting diets and reducing food waste could reduce agricultural land needs, and are therefore critical for enabling supply-side measures including reforestation, as well as decreasing $CH_4$ and $N_2O$ emissions from agriculture.

- In the AR6, WGIII assessed as medium evidence, there is medium agreement that the likely range of global land -based economic mitigation potential is approximately 8–14 Gt$CO_2$-eq/yr up to USD 100 t$CO_2$-eq-1 between 2020 and 2050 which is about half of the technical potential (Nabuurs ***et al.,*** 2022)7i). The global economic potential estimates in this assessment are slightly higher than in the range of estimates in the Fifth Assessment Report (AR5).

- Several barriers to the implementation of climate change mitigation measures that have been identified relate to production, diversity of agricultural systems, lack of funding, knowledge gaps and lack of international collaboration, which all highlight the difficulties and challenges in understanding the full extent of the mitigation potential available in the agrifood sector. For instance, increasing demand for food and animal source protein, particularly in developing countries, and associated pressure to increase productivity generally requires increased inputs, which leads to increased emissions. Uncertainty, differences in local conditions, and difficulty in accessing technology and data are also key barriers (Nabuurs ***et al.***, 2022).

- Mitigation and adaptation can have important implications for vulnerable people and communities. The number of hungry and food-insecure people in the world is rapidly growing; in 2021, it was estimated that nearly 2.3 billion people around the globe, i.e., 30 percent of the world population, were moderately or severely suffering from food insecurity (FAO *et al.,* 2022). Due to the large number of farms in the world, it is essential to consider rural poverty and food insecurity in AFOLU mitigation.** It is important to better understand how different mitigation policies affect the poor. Accordingly, barriers to adoption of AFOLU mitigation will be strongest where there are historical practices and long -standing traditions (Nabuurs ***et al.***, 2022).

Notes

* The term 'agrifood systems' is defined by FAO as "a set of actions that are interlinked". Farming, harvesting, fishing, livestock-rearing, storing, processing, transporting, selling, buying, eating, and disposing of our food are all part of these complex systems, which can include non-food products that come from agriculture such as cotton and forest products.

** "Barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects" (IPCC 2022a).

# What is new in the Sixth Assessment Report? 1

The agrifood sector has encountered major changes as highlighted in this AR6. More precisely, the AFOLU chapter assesses GHG fluxes and their associated drivers, mitigation options and policies, at time scales of 2030 and 2050 (Nabuurs *et al.,* 2022).

The overall aim is to assess the latest estimated mitigation potential of available measures taking into consideration not only technical, but also economic feasibility. It also considers how to realize the mitigation potential while minimizing trade-offs and risks, and maximizing co-benefits that can enhance food security, conserve biodiversity and address other challenges (Nabuurs *et al.,* 2022).

## ASSESSMENT OF MITIGATION MEASURES

Regarding the assessment of mitigation measures, the report outlines relevant activities, co-benefits, risks, implementation opportunities, costs and barriers. It also provides a summary of conclusions from previous IPCC reports, namely AR5, (IPCC, 2014), and the Special report on climate change and land (SRCCL) (IPCC, 2019), followed by the latest findings and developments since then. For each technical area, assessments and conclusions are highlighted by presenting quantitative data on technical and economic potential.

The AFOLU chapter also provides a comprehensive assessment on how to realize the estimated mitigation potential while minimizing trade-offs and risks, and maximizing co-benefits to enhance food production, conserve biodiversity and address other challenges. (IPCC, 2022c).

## THE FOOD SYSTEMS APPROACH

Chapter 12 dedicates an entire section on food systems,[3] comprehensively reviewing recent estimates of food system emissions, and assessing mitigation options and opportunities beyond the AFOLU sector. This indicates that there is growing interest in the literature on the food system approach, which was introduced in the IPCC SRCCL.

A food system approach allows to identify cross-sectoral opportunities including technological and behavioural options, and also to evaluate broader policies whose primary targets are not only producers and consumers, but also other stakeholders involved in food systems with possibly higher mitigation efficiency (Babiker *et al.,* 2022).

[3] The food systems includes all food chain activities (production, processing, distribution, preparation, consumption of food) and the management of food and wastes, as well as institutions and infrastructures influencing any of these activities.

## TECHNOLOGIES

There is a rich description of individual technologies compared to that in AR5 for those ready for large -scale deployment and use, as well as new and emerging technologies such as digital agriculture and food technologies. Knowledge gaps, research needs and areas that need prioritization are also elaborated upon throughout the report. This kind of assessment proves highly useful for policymakers, researchers, practitioners and investors to develop or update their short- and long-term plans as well as their national GHGs reduction targets.

This is even more important because it is noted with high confidence that "AFOLU mitigation measures have been well understood for decades, however, deployment remains slow and emission trends indicate unsatisfactory progress." (Nabuurs *et al.,* 2022). Accordingly, enabling rapid and effective action is essential considering that "the AFOLU sector can provide 20–30 percent of the global mitigation needed for a 1.5 °C or 2 °C pathway towards 2050 (robust evidence, medium agreement)" (Pathak *et al.,* 2022).

## BOX 2.

### Technical and economic mitigation potential

In IPCC assessment reports, the mitigation potential for AFOLU measures is estimated by calculating the scale of emissions reduction and/or carbon sequestration against a counterfactual scenario without mitigation activities.

The report mainly categorizes this mitigation potential from two angles:

- the technical mitigation potential, which refers to the biophysical potential or possible amount of emissions reduction with current technologies; and
- the economic mitigation potential, which refers to the mitigation estimated to be possible at an annual cost of up to USD 100 per $tCO_2$-eq mitigated. This cost is considered the price that society is willing to pay for mitigation and is used as a proxy to estimate the proportion of technical mitigation potential that could realistically be implemented.

Economic mitigation potential estimates may be more relevant for policymaking than technical mitigation potential because the latter reflects a theoretical maximum that may not be feasible or sustainable. However, cost is not only one constraint to mitigation, and the realization of economic potential depends on multiple context -specific environmental and socio-cultural factors (discussed in *4. Barriers to implementation* of this report).

# Emissions and trends at a glance

# 2

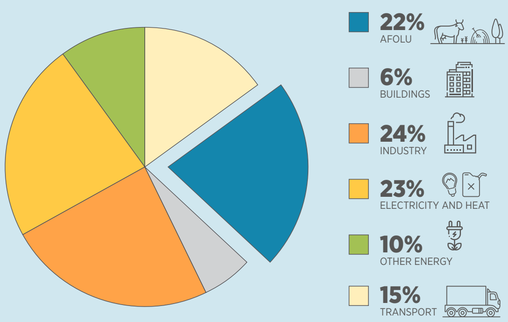
## EMISSIONS OVERVIEW

Between 2010 and 2019, the global net anthropogenic GHG emissions marked a historic record high and continued to rise across all sectors and subsectors (Dhakal *et al.,* 2022). Indeed, emissions were on the rise and kept growing throughout the period 2010–2019 averaging annual GHG emissions of 56 $GtCO_2$-eq $yr^{-1}$, as follows:

- "The AFOLU sector, on average, accounted for 13–21 percent of global total GHG emissions in the period 2010–2019. At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic $CO_2$ emissions". (Pathak *et al.,* 2022). Indeed, "AFOLU $CO_2$ emission fluxes are driven by land use change and the rate of deforestation, which accounts for 45 percent of total AFOLU emissions, has generally declined." (Nabuurs *et al.,* 2022).
- In 2019, GHG emissions from AFOLU reached 13 $GtCO_2$-eq globally accounting for 22 percent of total global GHG emissions, comprising emissions from agriculture and forestry and other land uses. (Dhakal *et al.,* 2022).

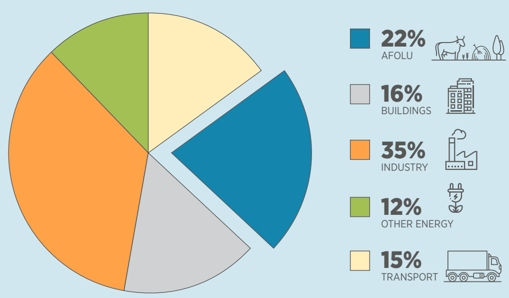
Direct emissions are physically arising from activities within well-defined boundaries of a specific sector. Indirect emissions are arising as a consequence of activities within well-defined boundaries but occuring outside the specified boundaries. In Figure 2, each sector includes indirect emissions linked to the use of heat and electricity production outside of the boundaries of the economic sector.

**FIGURE 1. Direct emissions $GtCO_2$-eq by sector, 2019**




Source: **Dakal, S. *et al.*** 2022. *Emission Trends and Drivers.* Cambridge and New York. Cambridge University Press.

**FIGURE 2. Direct and indirect emissions $GtCO_2$-eq by sector, 2019**




Source: **Dakal, S. *et al.*** 2022. *Emission Trends and Drivers.* Cambridge and New York. Cambridge University Press.

## MAJOR TRENDS

### Food systems

Twenty-three to forty-two percent of global GHG emissions are associated with food systems, while there is still widespread food insecurity and malnutrition. Absolute GHG emissions from food systems increased from 14 to 17 $GtCO_2$-eq yr-1 in the period 1990-2018. Both supply- and demand-side measures are important to reduce the GHG intensity of food systems (Pathak *et al.*, 2022).

### Livestock

There is a general trend of intensification, including in livestock production, whereby less grazing land is supporting increasing livestock numbers in conjunction with greater use of crops as livestock feed (Pathak *et al.*, 2022). Overall, enteric fermentation dominates agricultural emissions, which are associated with the number of ruminant animals and productivity. Both $CH_4$ and $N_2O$ emissions from manure management and deposition on pastures, contribute to making livestock the main agricultural emissions source worldwide (Pathak *et al.*, 2022). The data show "continued global livestock population growth between 1990 and 2019, including increases of 18 percent in cattle and buffalo numbers, and 30 percent in sheep and goat numbers, corresponding with $CH_4$ emission trends" (Nabuurs *et al.,* 2022).

### Irrigated and flooded rice cultivation

Rice cultivation is an important source of GHG emissions, and in particular, its expansion is an important driver in $CH_4$ emissions. Indeed, "global rice production is projected to increase by 13 percent by 2028 compared to 2019 levels" (Nabuurs *et al.,* 2022). During the period between 2010 and 2019, emissions from rice cultivation were higher than in any previous decade. At the regional levels, between 1990 and 2019, Africa has recorded the most important increase of 160 percent in area under rice cultivation, followed by Asia and the Developing Pacific (+6 percent), with area reductions evident in all other regions (Nabuurs *et al.,* 2022). Changes in geographical pattern in emissions have been observed in response to the trends in global production and consumption of rice. Indeed, "data indicate that the greatest growth in rice consumption between 1990 and 2013 occurred in Eastern Europe and West Central Asia (+42 percent) followed by Africa (+25 percent), with little change (+1 percent) observed in Asia and the Developing Pacific." (Nabuurs *et al.,* 2022).

### Synthetic Fertilizers

At the global level, the use of synthetic nitrogen fertilizers has been on the rise since the 1970s, contributing to elevated $N_2O$ emissions. Along the same line, recent data show a 41 percent increase in global nitrogen fertilizer use between 1990 and 2019 corresponding to increased $N_2O$ emissions, which can be explained by the desire to obtain increased crop yields. This is illustrated by a 61 percent increase in average global cereal yield per hectare observed during the same period, achieved through both increased fertilizer use and varietal improvements (Nabuurs *et al.,* 2022). Increased yields are in response to increased demand for food, fuel and fibre crops strongly associated with a growing human global population.

## BOX 3.

### Emissions reporting on agriculture and land use, land-use change and forestry

Under the enhanced transparency framework of the Paris Agreement, countries must use the 2006 IPCC guidelines to develop their national greenhouse gas inventory; however, there must be separate reporting of GHG inventory information on agriculture and land use, land-Use change and forestry (LULUCF). Fluxes of $CO_2$ are predominantly reported under LULUCF, and fluxes of $CH_4$ and $N_2O$ from agricultural land are predominantly reported under agriculture.

# Research, development and mitigation potential in agrifood systems

3

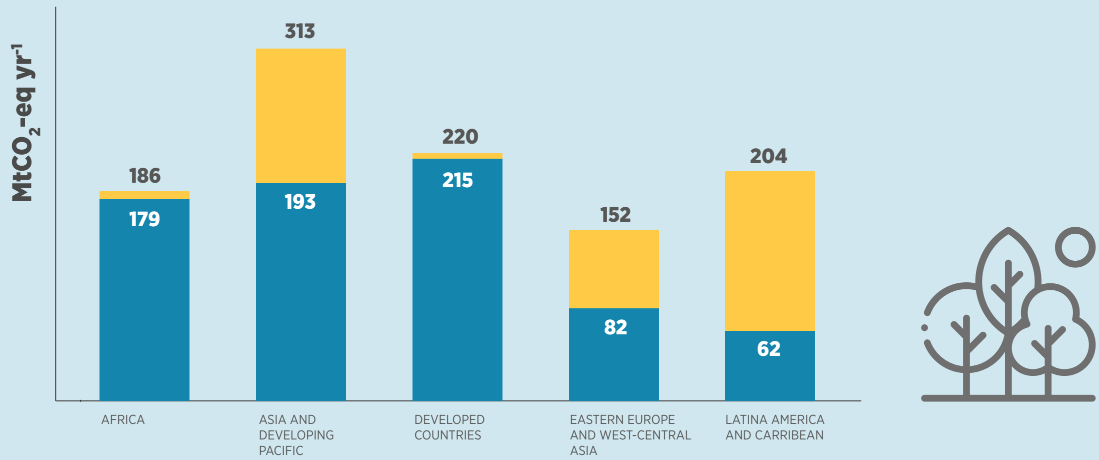
## FOREST

The global technical mitigation potential of afforestation and reforestation activities by 2050 is 3.9 (0.5–10.1) $GtCO_2$ $yr^{-1}$, and the economic mitigation potential (< USD 100 $tCO_2$) is 1.6 (0.5–3.0) $GtCO_2$ $yr^{-1}$ (Nabuurs *et al.,* 2022).

Improved forest management activities have important mitigation potential. Indeed, at the regional level, economic mitigation potential estimated at USD 100 $tCO_2$ has 179–186 $MtCO_2$-eq $yr^{-1}$ in Africa, 193–313 $MtCO_2$-eq $yr^{-1}$ in Asia and Developing Pacific, 215–220 $MtCO_2$-eq $yr^{-1}$ in developed countries, 82–152 $MtCO_2$-eq $yr^{-1}$ in Eastern Europe and West-Central Asia, and 62–204 $MtCO_2$-eq $yr^{-1}$ in Latin America and Caribbean. In North America, it is estimated that in the next 30 years, forest management could contribute to the reduction of 154 $MtCO_2$ $yr^{-1}$ in the United States of America and Canada, with 81 $MtCO_2$ $yr^{-1}$ available at less than USD 100 $tCO_2$. In Europe, climate-smart forestry could mitigate an additional 0.19 $GtCO_2$ $yr^{-1}$ by 2050 (Nabuurs *et al.,* 2022).

Improved forest management activities consist of one or combination of longer rotations, less intensive harvests, continuous cover forestry, mixed stands, more adapted species, selected provenances, high quality wood assortments, etc. These measures can lead to higher forest carbon stocks, better quality of produced wood, and continuous production of wood joints with the enhancement and maintenance of the forest carbon stock.

**FIGURE 3. Economic mitigation potential of forest management activities estimated by 2050 at regional level**




Source: **Nabuurs *et al.*** 2022. *Agriculture, Forestry and Other Land Uses (AFOLU).* Cambridge and New York. Cambridge University Press.

## AGRICULTURE

### Soil carbon management in croplands and grasslands

Soil carbon management in croplands refers to agricultural management practices, including improved crop management, nutrient management, reduced tillage intensity and residue retention, improved water management, use of cover crops, organic matter application, improved rice management and biochar application. As regards grasslands, the practices include management of vegetation; livestock management; fire management (Nabuurs *et al.,* 2022).

Soil carbon management is of primary importance due to its elevated mitigation potential in agriculture. Indeed, enhanced soil carbon management in croplands has a global technical mitigation potential of 1.9 (0.4–6.8) $GtCO_2$ $yr^{-1}$ and an economic mitigation potential of 0.6 (04–0.9). In grasslands, the technical potential is of 1.0 (0.2–2.6) $GtCO_2$ $yr^{-1}$, and the economic potential is 0.9 (0.3–1.6) $GtCO_2$ $yr^{-1}$.

Practices of soil carbon management in croplands can be replicated in many different ecosystems, although their effectivity appears limited in arid regions (IPCC, 2022a). Conversely, practices have greater capacities in areas where grasslands have been degraded and soil organic carbon is depleted. Estimates highlight important economic potential between 2020 and 2050 for croplands in Asia and the Developing Pacific (339.7 $MtCO_2$ $yr^{-1}$) and for grasslands, in developed countries (253.6 $MtCO_2$ $yr^{-1}$) (Nabuurs *et al.,* 2022).

### Biochar

Biochar is produced by heating organic matter in oxygen-limited environments (pyrolysis and gasification) (Nabuurs *et al.,* 2022). It has significant mitigation potential through carbon dioxide removal (CDR) and emissions reduction, and can also improve soil properties, enhancing productivity and resilience to climate change. When applied to soils, biochar is estimated to persist from decades to thousands of years, depending on feedstock and production conditions.

According to data estimates, the biochar system with the greatest economic mitigation potential between 2020 and 2050 is located in Asia and the Developing Pacific (793 $MtCO_2$ $yr^{-1}$), followed by developed countries (447 $MtCO_2$ $yr^{-1}$). Mitigation through biochar use will be greatest where biochar is applied to responsive soils (acidic, low fertility), where soil $N_2O$ emissions are high and where the syngas co-product displaces fossil fuels.

Biochar has a technical potential of 2.6 (0.2–6.6) $GtCO_2$-eq $yr^{-1}$ of which 1.1 (0.3–1.8) $GtCO_2$-eq $yr^{-1}$ is available up to USD 100 $tCO_2$ –1. However, it should be noted that mitigation and agronomic co-benefits depend strongly on biochar properties and the soil to which biochar is applied (Nabuurs *et al.,* 2022).

### Agroforestry

Agroforestry is a set of diverse land management systems that integrate trees and shrubs with crops and /or livestock in space and/or time. The mitigation potential of agroforestry systems is widely recognized. In fact, agroforestry accumulates carbon in woody vegetation and soil, and offers multiple co-benefits such as increased land productivity, diversified livelihoods, reduced soil erosion and improved water quality (Nabuurs *et al.,* 2022).

“Consideration of carbon sequestration in the context of food and fuel production, as well as environmental co-benefits at the farm, local and regional scales can further help support decisions to plant, regenerate and maintain agroforestry systems.” (Nabuurs *et al.,* 2022).

Recent data estimate technical potential of 9.4 $GtCO_2$-eq $yr^{-1}$ of agroforestry on 1.87 and 1.89 billion ha of crop and pasture lands (Nabuurs *et al.,* 2022). Regional estimates of mitigation potential are scant, with agroforestry options differing significantly by geography. Agroforestry has a technical potential of 4.1 (0.3–9.4) $GtCO_2$-eq $yr^{-1}$ for the 2020–2050 period, of which 0.8 (0.4–1.1) $GtCO_2$-eq $yr^{-1}$ is available at USD 100 $tCO_2$-eq $yr^{-1}$ (Nabuurs *et al.,* 2022).

### Enteric Fermentation

Methane from enteric fermentation is a by-product of the natural digestive process occurring in ruminant animals such as cattle, goats, sheep, and buffalo (FAO, 2023). Mitigating methane emissions from enteric fermentation can consist of direct measures such as targeting ruminal methanogenesis and emissions per animal or units of feed consumed, or indirect measures of increasing production efficiency. These measures can be classified as those relating to (i) feeding; (ii) supplements. additives and vaccines; and (iii) livestock breeding and wider husbandry (Nabuurs *et al.,* 2022).

In concrete terms, chemically synthesized inhibitors are promising, emerging near-term measures with high mitigation potential reported (16–70 percent) and commercial availability expected within two years in some countries. However, their mitigation persistence, cost and public acceptance or regulatory approval is currently unclear while administration in pasture-based systems is likely to be challenging. $CH_4$ vaccines are still under development (Nabuurs *et al.,* 2022).

At the regional level, developed countries generally focus on direct technical options, while developing countries tend to emphasize improving efficiency. Studies using a range of IPCC GWP100 values for $CH_4$ reveal that activities to reduce enteric $CH_4$ emissions have a global technical potential of 0.8 (0.2–1.2) $GtCO_2$-eq $yr^{-1}$, of which 0.2 (0.1–0.3) $GtCO_2$-eq $yr^{-1}$ is available up to USD 100 $tCO_2$-$eq^{-1}$ (Nabuurs *et al.,* 2022).

### Improved rice management

Emissions from rice cultivation mainly concern $CH_4$ associated with anaerobic conditions (i.e. flooded fields), while $N_2O$ emissions also occur via nitrification and denitrification processes. Measures to reduce $CH_4$ and $N_2O$ emissions include improved water management [e.g. single and multiple drainage practices such as alternate wetting and drying (AWD)]: improved residue management; improved fertilizer application; and soil amendments. These measures not only have mitigation potential, but can also improve water use efficiency, reduce overall water use, enhance drought adaptation and overall system resilience, improve yield, reduce production costs of seeds, pesticide, pumping and labour, increase farm income, and promote sustainable development (Nabuurs *et al.,* 2022).

However, some studies have reported that water management can increase $N_2O$ emissions while reducing $CH_4$ emissions, potentially off-setting some mitigation benefits while the effects on $N_2O$ emissions are variable depending on site-specific factors such as weather, fertilizer and organic matter inputs. Further, both yield reduction and improvement have been reported associated with AWD. (Nabuurs *et al.,* 2022).

At the regional level, variations in $CH_4$ emissions range from 0.5 to 41.8 mg/m$^2$/hr in Southeast Asia, 60 to 0.5–37.0 mg/m$^2$/hr in Southern and Eastern Asia, 61 and to 0.5 to 10.4 mg/m$^2$ /hr in North America. Overall, improved rice management has a technical potential of 0.3 (0.1–0.8) $GtCO_2$-eq yr$^{-1}$, and an economic potential of 0.2 (0.05–0.3) $GtCO_2$-eq yr$^{-1}$ between 2020 and 2050 (Nabuurs *et al.,* 2022). Improving rice cultivation practices will not only reduce GHG emissions but will also improve production sustainability in terms of resource utilization, including water consumption and fertilizer application, when carefully designed according to local conditions and cultivation practices.

### Crop nutrient management

Improved crop nutrient management can reduce $N_2O$ emissions from cropland soils. Practices include optimizing fertilizer application delivery, rates and timing, utilizing different fertilizer types, and using slow or controlled-released fertilizers or nitrification inhibitors (Nabuurs *et al.*, 2022).

In addition to individual practices, integrated nutrient management that combines crop rotations, including intercropping, nitrogen biological fixation, reduced tillage, use of cover crops, manure and bio-fertilizer application, soil testing and comprehensive nitrogen management plans, is central for optimizing fertilizer use, enhancing nutrient uptake and potentially reducing $N_2O$ emissions. Tailored nutrient management approaches are implemented in contrasting farming systems and contexts and are supported by best management practices to balance and match nutrient supply with crop requirements, provide greater stability in fertilizer performance and to minimize $N_2O$ emissions and nutrient losses from fields and farms (Nabuurs *et al.*, 2022).

These approaches can incur a risk of yield reduction under certain circumstances, and practices may not be accessible or adequate to certain regions. Nonetheless, crop nutrient management has a technical potential of 0.3 (0.06–0.7) $GtCO_2$-eq yr$^{-1}$, of which 0.2 (0.05–0.6) $GtCO_2$-eq yr$^{-1}$ is available up to USD 100 $tCO_2$-eq$^{-1}$ (medium confidence). Indeed, co-benefits of improved nutrient management can include enhanced soil quality, carbon sequestration in soils and biomass, soil water holding capacity, adaptation capacity, crop yields, farm incomes and water quality, and in certain cases, it may facilitate land sparing (Nabuurs *et al.*, 2022).

### Manure management

Manure management measures aim to mitigate $CH_4$ and $N_2O$ emissions from manure storage and deposition. Mitigation of $N_2O$ considers both direct and indirect (i.e. conversion of ammonia and nitrate to $N_2O$) sources. Implementation of manure management measures with other livestock and soil management measures can enhance system resilience, sustainability, food security and help prevent land degradation, and can also benefit the localized environment. Indeed, manure management measures have a global technical potential of 0.3 (0.1–0.5) $GtCO_2$-eq yr$^{-1}$, of which 0.1 (0.09–0.1) $GtCO_2$-eq yr$^{-1}$ is available at up to USD 100 $tCO_2$-eq-1 (medium confidence). There is robust evidence and high agreement that there are measures that can be applied in all regions (Nabuurs *et al.*, 2022).

Country-specific studies provide insight into regionally applicable measures, with an emphasis on small -scale anaerobic digestion, solid manure coverage and daily manure spreading in Asia and the Developing Pacific, and Africa. Tank/lagoon covers, large-scale anaerobic digestion, improved application timing, nitrogen inhibitor application to urine patches, soil-liquid separation, reduced livestock nitrogen intake, trailing shoe, band, or injection slurry spreading, and acidification are emphasized in developed countries.

### Farming systems

Several farming systems approaches have important mitigation potential. In fact, there is robust evidence and high agreement that agriculture needs to change to facilitate environment conservation while maintaining and where appropriate, increasing overall production. The approaches below are concrete examples of effective farming systems. Mitigation from these approaches may result from either emissions reduction or enhanced carbon sequestration, via combinations of management practices.

### Agroecology and regenerative agriculture

Agroecology[4] as a farming system is gaining ground at the global level. Indeed, there is limited discussion on its mitigation potential but robust evidence that it can improve system resilience and bring multiple co-benefits. Although there is limited evidence of its mitigation capacity, increasing studies on specific agroecological practices suggest that the agroecology system may have mitigation potential. There is medium confidence that regenerative agriculture is also gaining attention and share principles of agroecology and is likely to contribute to mitigation (Nabuurs *et al.*, 2022).

### Conservation agriculture and organic farming

Recent research generally agrees that conservation agriculture has the greatest mitigation potential in dry areas. This farming system has the capacity to facilitate improved nitrogen use efficiency. There is high confidence that conservation agriculture has adaptation benefits, and there is wide agreement that it can enhance system resilience to climate-related stress, notably in dry regions, and strong evidence that it can contribute to mitigation; however, its contribution depends on multiple factors, including climate and residue returns (high confidence) (Nabuurs *et al.*, 2022).

Organic farming is guided by specific principles and associated regulations and may be noted more for potential co-benefits, such as enhanced system resilience and biodiversity promotion than mitigation. Several studies have reviewed the emissions footprint of organic farming compared to conventional systems, and most evidence suggests that organic production typically generates lower emissions per unit of area, while emissions per unit of product vary and depend on the produce. Although context -specific, organic farming is reported to typically generate lower yields. It has also been suggested to increase soil carbon sequestration, although definitive conclusions are challenging (Nabuurs *et al.*, 2022).

### Other emerging technologies in the agrifood sector

Fast advancing technologies shape production and consumption, and drive land-use patterns and terrestrial ecosystems at various scales. Innovation is expected to help drive increases in global crop production during the next decade. For example, emerging gene editing technologies may advance crop breeding capabilities, however, are subject to biosafety, public acceptance, and regulatory approval.

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[4] In the report, agroecology is described as a dynamic and prolific concept and farming system that can improve resilience and bring multiple co-benefits, which is different from FAO's 10 elements of agroecology.

In Asia, technological development changed agriculture with significant improvements in production and climate change adaptation. Developments such as precision agriculture and drip irrigation have facilitated more efficient agrochemical and water use (Nabuurs *et al.*, 2022).

Emerging food technologies, such as cellular fermentation, cultured meat and controlled environment agriculture, can bring a substantial reduction in direct GHG emissions from food production (limited evidence, high agreement). These technologies have lower land, water and nutrient footprints, and address concerns over animal welfare. Realizing the full mitigation potential depends on access to low-carbon energy as some emerging technologies are more energy-intensive. This also holds for the deployment of cold chain and packaging technologies, which can help reduce food loss and waste, but increase energy and material use (Nabuurs *et al.*, 2022).

## DEMAND-SIDE MEASURES

### Shift to sustainable healthy diets

For the IPCC, the term 'sustainable healthy diets' refers to "dietary patterns that promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable" (Nabuurs *et al.*, 2022).

In addition to climate mitigation gains, a transition towards more plant-based consumption and reduced consumption of animal-based foods, particularly from ruminant animals, could reduce pressure on forests and land used for feed, support the preservation of biodiversity and planetary health, and contribute to preventing forms of malnutrition in developing countries (Nabuurs *et al.*, 2022). Indeed shifting toward sustainable and healthy diets requires effective food-system-oriented reform policies that integrate agriculture, health and environment policies to comprehensively address synergies and conflicts in cross -cutting sectors of agriculture, trade, health, environment protection, etc. and to capture spillover effects.

"Shifting towards diets that exclude animal-based food could reduce land use by 3.1 billion ha, decrease food-related GHG emissions by 6.5 $GtCO_2$-eq $yr^{-1}$, acidification by 50 percent, eutrophication by 49 percent, and freshwater withdrawals by 19 percent for a 2010 reference year" (Nabuurs *et al.*, 2022).

**FIGURE 4. Potential main benefits of sustainable healthy diets**


Source: **Nabuurs *et al.*** 2022. *Agriculture, Forestry and Other Land Uses (AFOLU).* Cambridge and New York. Cambridge University Press.

Based on studies to date, shifting towards sustainable healthy diets has a technical potential that includes savings in the full value chain of 3.6 (0.3–8.0) $GtCO_2$-eq $yr^{-1}$, of which 2.5 (1.5–3.9) $GtCO_2$-eq $yr^{-1}$ is considered plausible (medium confidence). Shifting to sustainable healthy diets has important potential to achieve global GHG mitigation targets as well as public health and environmental benefits (high confidence) (Nabuurs *et al.*, 2022).

## Reduction of food loss and waste

Food loss and waste (FLW) refer to the edible parts of plants and animals produced for human consumption that are not ultimately consumed. Food loss occurs through spoilage, spilling or other unintended consequences due to limitations in agricultural infrastructure, storage and packaging (Nabuurs *et al.*, 2022). Food waste typically occurs at the distribution and consumption stages in the food supply chain and refers to food that is appropriate for human consumption that is discarded or left to spoil. The following options could help reduce FLW: increased investment in harvesting technologies in developing countries, incentives towards reducing business and consumer waste, introduction of mandatory FLW reporting and reduction targets targeting large corporations, awareness and education to induce behaviour change, regulation of unfair trading practices, etc. (Nabuurs *et al.*, 2022).

Not only does reducing FLW have the potential to free up to several millions $km^2$ of land (high confidence), but it is also considered as a mitigation measure that could substantially lower emissions, with estimated mitigation potential of 0.6–6.0 $GtCO_2$-eq $yr^{-1}$ in the food supply chain (Smith *et al.*, 2014).

Overall, reduced FLW has large global technical mitigation potential of 2.1 (0.1–5.8) $GtCO_2$-eq $yr^{-1}$, including savings in the full value chain and using 100-year global warming potential (GWP100) and a range of IPCC values for $CH_4$ and $N_2O$ (Nabuurs *et al.*, 2022).

## Improved and enhanced use of wood products

The use of wood products refers to the fate of harvested wood for material uses and includes two distinctly different components affecting the carbon cycle, including carbon storage in wood products and material substitution. When harvested, wood is used for the manufacture of wood products, carbon remains stored in these products depending on their end use and lifetime.

Carbon storage in wood products can be increased by enhancing the inflow of products in use, or effectively reducing the outflow of the products after use. This can be achieved through additional harvest under sustainable management, changing the allocation of harvested wood to long-lived wood products, or by increasing products' lifetime as well as recycling (Nabuurs *et al.*, 2022).

"The enhanced use of wood products could potentially activate or lead to improved sustainable forest management that can mitigate and adapt" (IPCC, 2022a, Ch.7). At production level, wood products from sustainably managed forests are associated with less greenhouse emissions in their production, use and disposal over their lifetime compared to products made from emission-intensive and non-renewable materials (strong evidence). The improved use of wood products has a technical potential of 1.0 (0.04–3.7) $GtCO_2$-eq $yr^{-1}$ and an economic potential of 0.4 (0.3–0.5) $GtCO_2$-eq $yr^{-1}$ (strong evidence and medium agreement) (IPCC, 2022c).

There is also strong evidence and high agreement at the product level that material substitution provides benefits for climate change mitigation since wood products are associated with less fossil-based GHG emissions over their lifetime than those made from emission-intensive and non-renewable materials.

**TABLE 1. Technical and economic mitigation potential, by sub-sector**

| Sub-sector | Technical potential | Economic potential |
|---|---|---|
| Forest | 3.9 (0.5–10.1) $GtCO_2$-eq $yr^{-1}$ | 1.6 (0.5–3.0) $GtCO_2$-eq $yr^{-1}$ |
| Enhanced soil carbon management in croplands | 1.9 (0.4–6.8) $GtCO_2$-eq $yr^{-1}$ | 0.6 (04–0.9) $GtCO_2$-eq $yr^{-1}$ |
| Enhanced soil carbon management in grasslands | 1.0 (0.2–2.6) $GtCO_2$-eq $yr^{-1}$ | 0.9 (0.3–1.6) $GtCO_2$-eq $yr^{-1}$ |
| Biochar | 2.6 (0.2–6.6) $GtCO_2$-eq $yr^{-1}$ | 1.1 (0.3–1.8) $GtCO_2$-eq $yr^{-1}$ |
| Agroforestry | 4.1 (0.3–9.4) $GtCO_2$-eq $yr^{-1}$ | 0.8 (0.4–1.1) $GtCO_2$-eq $yr^{-1}$ |
| Enteric fermentation | 0.8 (0.2–1.2) $GtCO_2$-eq $yr^{-1}$ | 0.2 (0.1–0.3) $GtCO_2$-eq $yr^{-1}$ |
| Improved rice management | 0.3 (0.1–0.8) $GtCO_2$-eq $yr^{-1}$ | 0.2 (0.05–0.3) $GtCO_2$-eq $yr^{-1}$ |
| Crop nutrient management | 0.3 (0.06–0.7) $GtCO_2$-eq $yr^{-1}$ | 0.2 (0.05–0.6) $GtCO_2$-eq $yr^{-1}$ |
| Manure management | 0.3 (0.1–0.5) $GtCO_2$-eq $yr^{-1}$ | 0.1 (0.09-0.1) $GtCO_2$-eq $yr^{-1}$ |
| Shift to sustainable healthy diets | 3.6 (0.3–8.0) $GtCO_2$-eq $yr^{-1}$ | 1.7 (1–2.7) $GtCO_2$-eq $yr^{-1}$ |
| Reduction of food loss and waste | 2.1 (0.1–5.8) $GtCO_2$-eq $yr^{-1}$ | 0.5 (0.0–0.9) $GtCO_2$-eq $yr^{-1}$ |
| Improved and enhanced use of wood products | 1.0 (0.04 -3.7) $GtCO_2$-eq $yr^{-1}$ | 0.4 (0.3–0.5) $GtCO_2$-eq $yr^{-1}$ |

Source: **Nabuurs *et al.*** 2022. *Agriculture, Forestry and Other Land Uses (AFOLU).* Cambridge and New York. Cambridge University Press.

# Barriers to implementation 4

The AR6 recognizes many mitigation measures related to agrifood systems that are readily available and could be implemented at relatively low cost, and most of them without major construction or special infrastructure. However, as highlighted in the report, “AFOLU mitigation measures have been well understood for decades but deployment remains slow” (Pathak *et al.,* 2022).

In this context, the following section will present the main barriers to implementation highlighted in several chapters of the report relevant to agrifood systems and potential roles that FAO could play in providing solutions.

## THE SPECIFIC NATURE, DIVERSITY AND PRODUCTION DEMAND OF AGRICULTURAL SYSTEMS

Emissions from the agriculture are highly specific since they mostly stem from organic and inorganic material provided as inputs or output in the management of agricultural systems and are broken down through the natural metabolism of microorganisms, which releases significant amounts of $CO_2$, $CH_4$ and $N_2O$ to the atmosphere (IPCC, 2014).

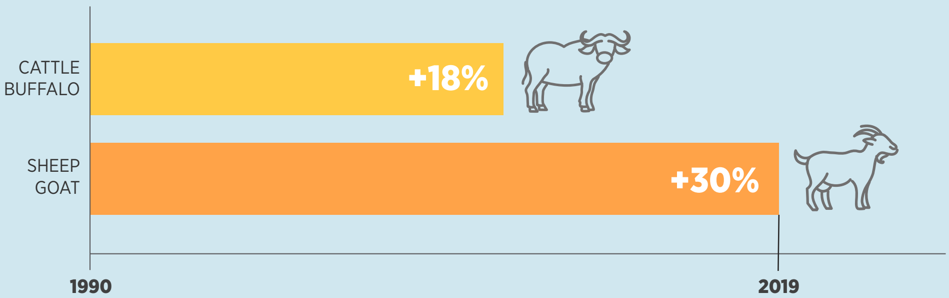
This process combined with the diversity in farming system can constitute impediments to the implementation of mitigation measures, because depending on the climate, scale and method applied, mitigation measures can positively or negatively affect its impact on biodiversity, ecosystem functioning, air quality, water availability and quality, soil productivity, and overall food security. Indeed, estimates indicate that an “overall ecosystem health is consistently declining with adverse consequences for good quality of life, human well-being, and sustainable development”, (Nabuurs *et al.,* 2022) which proves that greater efforts are needed in taking into consideration the specific nature of agricultural emissions (Pathak *et al.,* 2022).

Mitigating agricultural $CH_4$ and $N_2O$ emissions require considerable efforts as it faces various challenges, including cost, diversity and complexity of agricultural systems. Furthermore, these barriers and challenges for implementation are very context-specific and vary greatly following regions’ particularities. Differences in cultural values, governance, uncertain permanence effects, and the risk of reversal as well as limited access to technology, data and know-how are also barriers to implementation (IPCC, 2022a).

FAO’s new Strategy on Climate Change 2022–2031 emphasizes the need for a context-specific approach, refraining from providing uniform types of assistance to problems that have different origins and causes and that may require different means to achieve the common goals (FAO, 2022a).

Methane emissions from enteric fermentation are a main challenge. Data indicate continued global livestock population growth between 1990 and 2019, including increases of 18 percent in the number of cattle and buffalos, and 30 percent in the number of sheep and goats, which corresponds with $CH_4$ emission trends (FAO, 2022a).

**FIGURE 5. Global livestock population growth between 1990 and 2019**




Source: **FAO.** 2022a. *FAO Strategy on Climate Change. 2022–2031*. Rome. FAO.

Efforts have been made to increase production efficiency and decrease emission intensity. However, increased individual animal productivity generally requires increased inputs, which in turn generates increased emissions (FAO, 2022a). Manipulation of livestock diets, or improvements in animal genetics or health may counteract some of these emissions, whereas the production of inputs to facilitate increased animal productivity has the potential to indirectly drive further absolute emissions along the feed supply chain.

## LACK OF INTERNATIONAL COLLABORATION, LACK OF FUNDING AND NATIONAL CLIMATE POLICIES

The lack of resources committed to implementing AFOLU mitigation measures regarding alternative sources of income for rural households that rely on agriculture or forests for their livelihoods is a considerable barrier to implementation. Despite the recognition that the AFOLU sector has an important role in mitigation, the economic incentives needed to achieve AFOLU aspirations as per the Paris Agreement or to maintain temperatures below 2 °C have yet to emerge, and without consolidated efforts, the lack of funding to implement projects will continue to be a substantial barrier.

International cooperation among countries remains a challenge that needs to be overcome and "strengthened in several key respects in order to support mitigation action consistent with limiting temperature rise to below 2 °C in the context of sustainable development and equity" (Pathak *et al.,* 2022). Not only can international cooperation "enable developing countries to achieve their climate goals more effectively while also addressing other sustainable development goals" (Blanco *et al.,* 2022), but it is also "vital for achieving climate mitigation goals in the context of sustainable development" (Pathak *et al.,* 2022). Clearly, it constitutes a "critical enabler for achieving ambitious climate change mitigation goals" (IPCC, 2022a).

There is definitely a "large potential role for international cooperation to better address sector specific technical and infrastructure challenges that are associated with transformational changes needed to achieve the objectives of the Paris Agreement" (Patt *et al.,* 2022). FAO is described as one of the UN agencies implementing and supporting climate actions through technical assistance and capacity building. Mitigation measures specific to agricultural emissions still need to be concretely mainstreamed in climate policies at the national level. This is a challenge because "there is growing consensus that integration of adaptation and mitigation will advance progress towards sustainable development, and that ambitious mitigation efforts will reduce the need for adaptation in the long term" (Dubash *et al.,* 2022)

However, efforts to this end have been insufficient so far. Climate finance represents one concrete example and reports suggest that "once all countries have fully costed their nationally determined contributions (NDCs), the demand for (public and private) finance to support NDC implementation is likely to be orders of magnitude larger than funds available from bilateral and multilateral sources" (Patt *et al.,* 2022).

Hence, there is a marked need for integration and incorporation of mitigation measures in national climate policies. In implementing the new Climate Change Strategy 2022, FAO will contribute to the integration of agrifood systems in climate policies by supporting Members and partners in the identification, formulation, implementation and monitoring of relevant global and regional initiatives and pledges. The Organization is ready to enhance its support to member countries for climate action at the global, regional and local levels across agrifood systems, which is fundamental to their transformation (FAO, 2022b).

## BEHAVIOUR CHANGE

The AR6 describes consumers' behaviour change (e.g. adopting plant-based alternatives to meat) as a key challenge. Indeed, behavioural changes in food systems are required for sustainable agriculture to become a reality, but a particular challenge lies in collective behavioral changes of a large number of farmers compared to a relatively small number of major players in other industrial sectors.

Several factors such as "religion, values, culture, gender, identity, social status and habits strongly influence individual behaviours and choices and therefore, sustainable consumption" (Grubb *et al,* 2022). The new FAO Climate Change Strategy recognizes the importance of the behavioural sciences as a tool to provide new insights on lowering the barriers to take necessary climate action (FAO, 2022b).

## KNOWLEDGE AND DATA GAPS

Knowledge and data gaps are a major challenge for implementing mitigation measures and for scaling up climate action in agrifood systems. Among them, the shortage of data and lack of reliability are main constraint for many developing countries (FAO, 2022b). Indeed, "data quality and reporting frequency remains an issue particularly in developing countries where the statistical infrastructure is not well developed" (Dhakal *et al.,* 2022).

Furthermore, reporting lines regarding GHG emissions remain a problem because "global GHG emissions estimates are published less frequently and with greater reporting lags than, for example, $CO_2$ from fossil fuel and industry" (Dhakal *et al.,* 2022) and "uncertainties and their methodological treatment in GHG emissions estimates are still not comprehensively understood" (Dhakal *et al.,* 2022).

Filling these knowledge gaps will require strong commitment, and also interdisciplinary and international collaboration (Dhakal *et al.,* 2022). As such, "addressing the many knowledge gaps in the development and testing of AFOLU mitigation measures and options can rapidly advance the likelihood of achieving sustained mitigation" (high confidence) (Nabuurs *et al.,* 2022).

# Conclusion

The WGIII AR6 provides important and key information on climate change mitigation and effective pathways to reach sustainable development and limit GHG emissions globally. It can be observed throughout the report that efforts in agrifood systems can facilitate mitigation by reducing GHG emissions, removing meaningful quantities of carbon from the atmosphere and by providing raw materials to enable mitigation within other important, interconnected sectors.

Hence, it is of primary importance to scale up climate action and measures in agrifood systems because, when appropriately implemented, this contributes to addressing some critical, wider challenges, as well as contributing to climate change adaptation. However, agrifood systems are inextricably linked to some of the most serious challenges that have ever faced humanity, such as large-scale biodiversity loss, environmental degradation and the associated consequences.

Thus, it is essential to foster an enabling environment for climate change mitigation in the AFOLU sector because it accounts for a considerable portion of the Earth's terrestrial area, while greatly influencing soil, water and air quality, biological and social diversity, the provision of natural habitats, and ecosystem functioning, consequently impacting many SDGs.

The WGIII AR6 has proven the importance of enabling and promoting continued research into novel and emerging mitigation measures and associated cost-efficiency. Finally, it has also highlighted the importance of developing specific measures and carrying out research on best practices regarding implementation and optimal agricultural land and livestock management at the regional and country levels.

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