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CLIMATE CHANGE

Update on scientific findings on the interactions between agriculture, food systems and climate change

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT

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Abbreviations and acronyms

AFOLU	agriculture, forestry and other land use
AI	artificial intelligence
APSIM	Agricultural Production Systems Simulator
BECCS	bioenergy with carbon capture and storage
BNE	background N_2O emissions
CDR	carbon dioxide removal
CHRIS	Compact High-Resolution Imaging Spectrometer
CPI	Climate Policy Initiative
CSA	climate-smart agriculture
CUE	carbon use efficiency
dNUI	dual nitrification and urease inhibitor
DSSAT	Decision Support System for Agrotechnology Transfer
EMIT	Earth Surface Mineral Dust Source Investigation
EnMAP	Environmental Mapping and Analysis Programme
EO	earth observation
EUR	euro
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO statistical database
GDP	gross domestic product
GHG	greenhouse gas
GI	grazing intensity
GIS	geographic information system
GPS	global positioning system

GtC	gigatonnes of carbon
GWP	global warming potential
HiVE	High-Precision Versatile Ecosphere
IAL	integrated agriculture—livestock (system)
IAM	integrated assessment model
IAS	integrated agricultural system
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
IMTA	integrated multitrophic aquaculture
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRF	integrated rice—fish (system)
LCA	life-cycle assessment
LMICs	low-and middle-income countries
LSTM	Land Surface Temperature Mission
LULUCF	land use, land-use change and forestry
LWIR	long-wave infrared
mid-IR	mid-infrared (or mid-wave infrared)
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDC	nationally determined contribution
NGHGIs	national greenhouse gas inventories
NPP	net primary production
OpTIS	Operational Tillage Information System
PBCM	process-based crop models
PRISMA	PRecursore IperSpettrale della Missione Applicativa
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal

SIDS	Small Island Developing States
SOC	soil organic carbon
SSP	shared socioeconomic pathway
SWIR	short-wave infrared
TRISHNA	Thermal InfraRed Imaging Satellite for High-resolution Natural resource Assessment
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNFSS	United Nations Food Systems Summit
WDR	water-saving and drought-resistant rice
WEFE	water—energy—food—ecosystem (nexus)
WUE	water-use efficiency
US	United States
USD	US dollar
VNIR	visible near infrared
WOFOST	World Food Studies Simulator

Measurements

cm	centimetre
CO_2e	carbon dioxide equivalent
CO_2-we	carbon dioxide warming equivalents
g	gram

Gt	gigatonne
GtC	gigatonnes of carbon
GtC/y	gigatonnes of carbon per year
$GtCO_2e$	gigatonnes of carbon dioxide equivalent
ha	hectare
kg	kilogram
kg/ha	kilograms per hectare
m^2	square metre
mg	milligram
$mgCH_4/m^2/h$	milligrams of methane per square metre per hour
Mg	megagram
Mg/ha/yr	Megagrams per hectare per year
Mha	million hectares
mol	mole
µmol	micromole
$\mu mol/m^2/s$	micromole per square metre per second
mm	millimetres
Mt	million tonnes
$MtCH_4$	million tonnes of methane
$MtCH_4/yr$	million tonnes of methane per year
$MtCO_2$	million tonnes of carbon dioxide
$MtCO_2/yr$	million tonnes of carbon dioxide per year
$MtCO_2e$	million tonnes of carbon dioxide equivalent
$MtCO_2e/yr$	million tonnes of carbon dioxide equivalent per year
MtN_2O	million tonnes of nitrous oxide
MtN_2O/yr	million tonnes of nitrous oxide per year
MtN_2O-N/yr	million tonnes of nitrous oxide expressed as nitrogen per year
Q_{10}	temperature sensitivity

ppb	parts per billion
ppm	parts per million
R_e	ecosystem respiration
t	tonne
t/ha	tonnes per hectare
tC/ha	tonnes of carbon per hectare
tC/ha/yr	tonnes of carbon per hectare per year
tCO_2e	tonnes of carbon dioxide equivalent

Chemical formulae

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2SO_4	sulphuric acid
NH_3	ammonia
N_2O	nitrous oxide
NO_X	nitrogen oxides
NO_3-	nitrate
SO_2	sulphur dioxide
$PM_{2.5}$	fine particulate matter

1. Purpose of the report

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This White Paper reports on the latest scientific findings related to agriculture, food systems and climate change. It builds on the Intergovernmental Panel for Climate Change (IPCC) Special Report on Climate Change and Land and the contributions of Working Groups II and II to the IPCC's Sixth Assessment Report (IPCC, 2019, 2022a, 2022b). Although not exhaustive, it examines what is new (since 2018) and what still needs to be researched in terms of agriculture and agrifood systems[1], as well as the impacts, adaptation and mitigation of climate change.

The paper aims to bring together, in one place, information that can be used by the Food and Agriculture Organization of the United Nations (FAO), other United Nations agencies, the global research community and the IPCC. One objective is to synthesize information that could inform future IPCC reports on interactions between agriculture, food systems and climate change.

In 2017, FAO and the IPCC held a joint Expert Meeting, the output of which informed the IPCC (2019) Special Report on Climate Change and Land. This White Paper will inform the agenda and discussion topics for a similar meeting to be held at FAO headquarters in Rome in 2026. The paper focuses on research work published since 2018, although it includes older work where explanation is required or where the topic discussed was not included in previous IPCC reports (for example, "food systems" and "aquatic food production" as specific research topics).

The paper is divided into 12 sections authored by leading experts from 26 countries. Section 2 provides background information on the current global situation in which agriculture and food systems should be considered in terms of climate change and greenhouse gas (GHG) emissions.

[1] Agrifood systems are systems that encompass the primary production of food and non-food agricultural products, as well as in food storage, aggregation, post-harvest handling, transportation, processing, distribution, marketing, disposal and consumption. Within agrifood systems, food systems comprise all food products that originate from crop and livestock production, forestry, fisheries and aquaculture, and from other sources, such as synthetic biology, that are intended for human consumption (FAO, 2023).

It also considers the current status of coastal and marine ecosystems. Sections 3–6 deal with soils, crops, livestock and integrated farming systems. Section 7 considers new research on the status of, and threats to, oceans and coastal areas, setting the scene for a consideration of aquatic food production in Section 8. Section 9 presents technological advances in remote sensing and artificial intelligence (AI) as they apply to our understanding of agriculture, food systems and climate change. Section 10 synthesizes work published specifically on the topic of food systems since 2019. Section 11 explores relevant policy and governance issues, including nationally determined contributions (NDCs). Lastly, Section 12 acknowledges the limitations of this report by mentioning some topics that have not been included, but, will be discussed at the forthcoming international meeting.

References - Section 1

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2. Framing and context

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2.1. STATUS UPDATE ON GLOBAL AGRICULTURE AND FOOD SYSTEMS SINCE 2019

2.1.1 FOOD, FIBRE AND FEED PRODUCTION

Humans appropriate one-quarter to one-third of the world's potential net primary production (NPP), that is, the NPP that would prevail in the absence of land use. This is split about equally between biomass harvest and changes in NPP due to land management. The current total amount of agricultural biomass harvested (from cropland and grazing) is around 6 gigatonnes of carbon per year (GtC/yr), around 50–60 percent of which is consumed by livestock. Forestry harvested for timber and wood fuel amounts to about 1 GtC/yr (Arneth *et al.*, 2019).

Agricultural production has generally increased over the past three decades:

TABLE 2.1. Increase in agricultural production from 1990 to 2022

Crop	Increase (%)
Cereals	61
Meat	98
Milk	71
Egg	150
Soybean and other feeds	206
Fibre	31
Bioenergy	76

Source: FAO. 2024. FAOSTAT: Agricultural production. [Accessed on 25 October 2024]. https://www.fao.org/faostat/en/#data

The increase in agricultural output has outpaced human population growth, meaning per capita production of agricultural goods has increased by 30 percent over the same period.

TABLE 2.2. Change in some production factors from 1990 to 2022

Production factor	Change (%)
Inorganic nitrogen fertilizer use	+40
Pesticide use	+104
Areas irrigated	+37 There is no irrigated land in FAOSTAT
Cropland area	+6
Permanent Meadows and Pasture area	-3

Source: FAO. 2024. FAOSTAT:
Fertilizer: Fertilizers by Nutrient dataset. https://www.fao.org/faostat/en/#data/RFN
Pesticides: Pesticides Use dataset. https://www.fao.org/faostat/en/#data/RP
Land Use and irrigation: Land Use dataset. https://www.fao.org/faostat/en/#data/RL
[all accessed on 25 October 2024]. https://www.fao.org/faostat/en/#data

Agricultural production consumes 6.7 percent of total renewable water resources (FAO, 2021). This corresponds to 70 percent of all withdrawals, although more than 40 percent of the world's rural population lives in water-scarce river basins (FAO, 2017).

Large-scale land acquisition totalled 35.1 million hectares (Mha) between 2000 and 2020[2], although it slowed in the latter half of the period[3].

Imports and exports

Although on average only 17 percent of all food by weight is currently traded internationally, the value of trade in food and agricultural commodities has grown eightfold over the past five decades, during which time agricultural production has tripled. Food trade plays an important role in the global distribution of nutrients (Global Panel on Agriculture and Food Systems for Nutrition, 2020).

Import penetration (that is, imports as a percentage of global production) has increased for all agricultural products.

TABLE 2.3. Imports and exports as a share of global production, 2022 vs 1990 (%)

Export weight over total production was:		
	1990	2022
Maize and products	15%	19%
Soybeans	24%	45%
Import weight over total consumption was:		
	1990	2022
Wheat and products	29%	59%
Rice and products	4%	15%
Meat	8%	15%
Milk, excluding butter	13%	35%
Fish, seafood	48%	42%

Source: FAO. 2024. FAOSTAT: Agricultural production. [Accessed on 25 October 2024]. https://www.fao.org/faostat/en/#data

[2] For further information please see: https://landmatrix.org/

[3] Two-thirds of this area was acquired in the first decade. https://landmatrix.org/

Among meat products, only chicken imports have remained flat as a share of consumption. However, import volumes have increased substantially, as global chicken consumption has more than doubled over the past 25 years (Smith and Glauber, 2020).

In contrast, whole and skimmed milk powder imports have risen in recent years as the use of imported protein concentrates has become increasingly common in food manufacturing and for reconstitution into liquid milk (Stads *et al.*, 2022).

Agricultural productivity

Growth in food production per capita is showing signs of slowing down, having peaked in about 2010. The slowdown is strongest in developing countries, where the growth of agricultural output declined from almost 4 percent per year in the 1990s to around 2 percent in the 2010s (Martin and Vos, 2024; USDA ERS,2022; Gautam *et al.*, 2022).

The slowdown in agricultural productivity growth can be attributed in part to climate change. A recent study by Ortiz-Bobea *et al.* (2023) estimates that climate change has reduced global agricultural productivity growth by 21 percent since 1961, equivalent to losing roughly a decade of productivity growth. The impacts have hit tropical agriculture hardest, with productivity declines of 40 percent or more in some areas.

2.1.2 FOOD DEMAND

The number of hungry people in the world rose from 564 million in 2015, when the Sustainable Development Goals (SDGs) were agreed, to 733 million in 2023 — around 9 percent of the global population (FAO *et al.*, 2024). Even if the world realized an unfettered economic recovery from shocks caused by the COVID-19 pandemic and the war in Ukraine without any major new upheavals to 2030, the goal of Zero Hunger would remain far out of reach (Martin and Vos, 2024).

Furthermore, next to persistent widespread undernourishment (in the sense of deficient food energy or calorie intake), an estimated 3 billion people worldwide cannot afford the cost of a healthy diet and are probably affected by micronutrient deficiencies, a condition termed "hidden hunger" (Martin and Vos, 2024).

Food demand is increasing continuously amid a growing human population and per capita consumption:

TABLE 2.4. Drivers and features of food demand from 2000 to 2022

Measure	Change (%)
Population	+30
Number of obese	+155
Number of underweight	-6
Calories per capita	+10
Share of cereals in energy supply	-5
Proteins per capita	+22
Share of animals in protein supply	+4
Iron deficiency	+16

Source: FAO. 2024. FAOSTAT: Suite of Food Security Indicators, Food & Diet, Population and Employment. [Accessed on 25 October 2024]. https://www.fao.org/faostat/en/#data/FS

Food loss

FAO (2019) estimates that about 13.2 percent of all food meant for human consumption is lost every year between the harvest and retail stages of food production. In addition, the United Nations Environment Programme (UNEP) (2021) estimates that 17 percent of food is wasted by households or retail and food services. With a remaining total effective food supply and use of 69.8 percent, the total loss equals USD 1 trillion annually (Martin and Vos, 2024).

2.1.3 CLIMATE CHANGE IMPACTS ON AGRICULTURE AND FOOD SYSTEMS

There are many routes by which climate change can impact food security. It can affect the amount of food being produced, for instance, be it through direct impacts on yields or through indirect effects on water availability and quality, pests and diseases, or pollination services. It can also change atmospheric carbon dioxide (CO_2) concentration, affecting biomass and nutritional quality. Food safety risks during transport and storage can also be exacerbated by the changing climate (Mbow *et al.*, 2019).

In 2024, climate-related shocks were the main drivers of food crises in 18 countries, with almost 72 million people facing high levels of food insecurity (FSIN and Global Network Against Food Crises, 2024). This was an increase of 27 percent from 2022 (when 56.8 million people in 12 countries suffered high levels of food insecurity). Twelve of these countries were in Africa, where 47.8 million people required urgent assistance, and five were in Latin America and the Caribbean, where 12.2 million needed urgent relief. In Pakistan, 11.8 million people faced high levels of acute food insecurity, primarily due to weather extremes.

The Scientific Group of the United Nations Food Systems Summit (UNFSS) and its research partners found that, over the last four to five decades, climate change has reduced global cereal yields by 2–5 percent, on average, compared with a scenario of no climate change (Mirzabaev *et al.*, 2022; Iizumi *et al.*, 2018). A similar drop of around 5 percent was found in regional studies of wheat and barley in Europe (Moore and Lobell 2015), wheat in India (Gupta, Somanathan and Dey, 2017), and maize in Africa, Central and Eastern Asia (Ray *et al.*, 2019) and Central and South America (Verón. de Abelleyra and Lobell, 2015). Higher losses of 5–20 percent were found for millet and sorghum yields in West Africa (Sultan, Defrance and Iizumi, 2019), while maize yields in eastern and southern Europe were estimated to be 5–25 percent lower (Agnolucci and De Lipsis, 2020). There is a growing body of literature documenting the negative impacts of climate change on the yields of legumes, vegetables and fruits in drylands, tropical and subtropical areas (Mbow *et al.*, 2019; Scheelbeek *et al.*, 2018). These losses in yields have occurred despite countries undertaking coping and adaptive actions (Mbow *et al.*, 2019).

Although extreme weather events have always posed a threat of disruption to food systems, climate change is increasing the likelihood of simultaneous crop failures in major crop-producing areas around the world (Anderson *et al.*, 2019; Heino *et al.*, 2020).

Another study (Ortiz-Bobea *et al.*, 2023) concluded that climate change had reduced global agricultural total factor productivity by about 21 percent since 1961, a slowdown equivalent to losing the last seven years of productivity growth. Though agriculture globally has grown more vulnerable to continued climate change, the effect is substantially more severe (a reduction of 26—34 percent) in warmer regions, such as Africa and Latin America and the Caribbean.

Consequently, the climate emergency makes it critical to rethink food systems (Development Initiatives, 2020) and take speedy action accordingly.

2.1.4 AGRIFOOD SYSTEMS' IMPACT ON CLIMATE CHANGE

FAO reported the following statistics on net GHG emissions from agrifood systems for 2020 (FAO, 2022):

- In 2020, global agrifood systems emissions were 16 $GtCO_2e$, an increase of 9 percent from 2000. Agrifood systems emissions as a share of total net emissions globally dropped from 38 percent in 2000 to 31 percent in 2020, as while absolute agrifood emissions grew, non-food emissions grew faster. Agrifood systems accounted for the largest share of emissions of all sectors in Africa (59 percent) and the lowest share of sectoral emissions in Asia (nearly 25 percent).
- The farm gate accounted for nearly half of all agrifood systems emissions globally, with pre- and post-production processes contributing one-third and land-use change generating one-fifth. At the regional level, farm-gate emissions were the largest component in Oceania (71 percent), Asia (50 percent) and the Americas (43 percent). Land-use change was the largest contributor in Africa (44 percent), while pre- and post-production processes were the largest contributor in Europe (53 percent).
- The emissions intensity of products varied between 1 CO_2e/kg and 30 CO_2e/kg for meat (with the lowest values for chicken meat and the highest for beef). The global farm-gate emission intensity of cow's milk was 1 CO_2e/kg, about 24 percent less than in 2000.
- Per capita emissions declined 15 percent from the start of the century to 2.0 tCO_2e in 2020, with the highest level of per capita emissions in Oceania (6.5 tCO_2e) and the lowest in Asia (1.4 tCO_2e).

2.1.5 FOOD SYSTEMS TRANSFORMATION

Global food systems are failing to address food insecurity and malnutrition in an environmentally sustainable way (Pörtner *et al.*, 2022). The net benefits of achieving food systems transformation have been estimated at USD 5 trillion to USD 10 trillion a year, equivalent to between 4 percent and 8 percent of global gross domestic product (GDP) in 2020 (Ruggeri *et al.*, 2024).

Food systems are highly diverse. Ambikapathi *et al.* (2022) group them into five categories[4], ranging from traditional systems using ancient practices to highly automated, industrial systems (FOLU, 2019; Hendriks *et al.*, 2021).

Many initiatives and much information have been produced on food systems transformation since 2019, with the aim of: i) providing sufficient, accessible, healthy food for the world's population to abolish hunger and undernutrition; ii) providing secure and sufficient income to all stakeholders (in particular, women and youth); iii) minimizing hidden social, economic and environmental costs (FAO, 2023)[5,6,7], which currently amount to a staggering USD 12.7 trillion per year (2020 PPP - Purchasing Power Parity) (FOLU, 2019; Hendricks *et al.*, 2021, 2023; Lord, 2023; Ruggeri *et al.*, 2024)[8,9,10]; iv) increasing climate resilience (by reducing net emissions and adapting to changing climate); and v) ensuring continuous progression towards the above goals in line with the changing socioeconomic and environmental context.

The transformation of food systems is instrumental in achieving all of the SDGs by 2030, as well as the goals of the Paris Agreement and beyond. The survival of human beings is at stake.

This is why the transformation of food systems is included in Action 3(c) of the United Nations Pact for the Future: to "promote equitable, resilient, inclusive and sustainable agrifood systems so that everyone has access to safe, affordable, sufficient and nutritious food" (United Nations General Assembly, 2024).

4 The five categories are: rural and traditional; informal and expanding; emerging and diversifying; modernizing and formalizing; and industrial and consolidated.

5 The annual external costs of GHG emissions from the global food system have been estimated at USD 1.5 trillion, the natural capital costs at USD 1.7 trillion and pollution, pesticides and antimicrobial resistance at USD 2.1 trillion (Hendricks *et al.* 2023)].

6 Also see the Hidden Costs of Food counter at: https://foodsystemeconomics.org/

7 The environmental hidden costs, while not exhaustive, constitute more than 25 percent of the quantified hidden costs and are equivalent to almost one-third of agricultural value added. They are mostly associated with GHG and nitrogen emissions and are relevant across all country income groups (Summary of various sources listed in the references)

8 Equivalent to 12 percent of global GDP in 2020 (Ruggeri *et al.*, 2024).

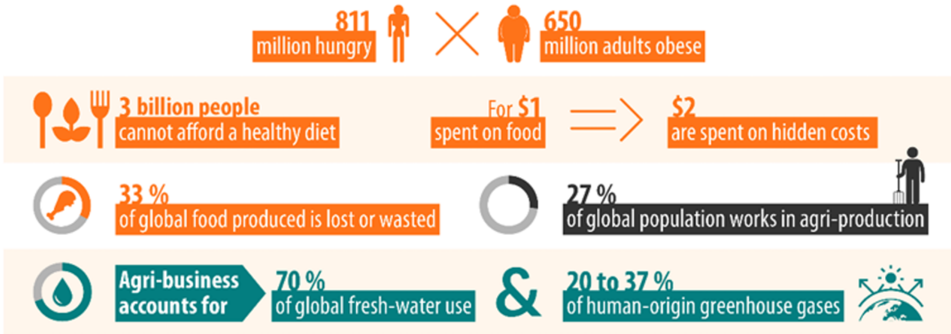
9 Compared with a global food systems market value of USD 10 trillion [annually] (FOLU, 2019).

10 Around 10 percent of global GDP, or between 8 percent and 12 percent of national GDP, [on average] (FAO, 2023).

United Nations Food Systems Summit

To advance the transformation of food systems, the UNFSS was held during the United Nations General Assembly in September 2021.

FIGURE 2.1. Why a food systems summit?



Source: European Parliamentary Research Service. 2021. United Nations Food Systems Summit 2021: Process, challenges and the way forward. Members' Research Service briefing. Brussels. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/696208/EPRS_BRI(2021)696208_EN.pdf

The UNFSS called on the United Nations system and all relevant stakeholders, including international financial institutions, the private sector and civil society, to support national mechanisms to develop and implement national pathways to 2030 that are inclusive and consistent with countries' climate commitments, building on national food systems dialogue. It identified five areas for action, driven by national governments, to bring about transformation: i) nourishing all people, ii) promoting nature-based solutions, iii) advancing equitable livelihoods, iv) building resilience and v) accelerating means of implementation. It emphasized the need for inclusive governance, financing and partnership, especially with regard to women, youth and Indigenous Peoples, and underscored the importance of integrating food systems into broader environmental and health agendas.

Following the UNFSS, countries will be supported by Resident Coordinators and United Nations country teams in developing and implementing national pathways for food systems, engaging all stakeholders. At the global level, the Rome-based Agencies — FAO, the International Fund for Agricultural Development (IFAD) and the World Food Programme (WFP) — will lead a coordination hub to support UNFSS outcomes by strengthening collaboration with key intergovernmental forums and enhancing technical and policy support for national food systems[ii]. Its key functions will include acting as a connector for national constituencies and the United Nations system, and as a catalyst of national action and support in relation to food systems transformation. It will also collaborate with the High Level Panel of Experts on Food Security of the Committee on World Food Security to improve science-policy integration.

[ii] The hub can be found at: https://www.unfoodsystemshub.org/en

The United Nations Secretary-General, supported by FAO, IFAD, WFP, the broader United Nations system and partners, will convene a global stocktaking meeting every two years to review progress on implementing the outcomes of the process and its contributions to the achievement of the 2030 Agenda. FAO hosted the first UNFSS+2 Stocktaking Moment in Rome in July 2023. The ensuing Secretary-General's report stated that the world was not on track to achieve food systems transformation, a key SDG accelerator (United Nations, 2023a). A preliminary assessment of the roughly 140 SDG targets with data showed only 15 percent or so are on track, with close to half moderately or severely off track and some 30 percent having seen no movement or regressed below the 2015 baseline (United Nations 2023a).

Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action

Furthermore, at the Twenty-eighth Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change (UNFCCC), 160 countries signed the Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action (COP28, 2023). These countries are home to more than 5.7 billion people and almost 500 million farmers, produce 70 percent of global food and are responsible for 76 percent of the world's emissions from food systems, or 25 percent of total global emissions. The Declaration stressed that any path to fully achieving the long-term goals of the Paris Agreement must include agriculture and food systems.

To achieve these goals, the Declaration emphasized the need to integrate agriculture and food systems into climate action, while also mainstreaming climate considerations into agricultural policies. The commitments include integrating agriculture and food systems into national adaptation plans, NDCs and long-term strategies prior to COP30. At COP29 a new "Baku Harmoniya Climate Initiative for Farmers"[12] has been launched to empowering farmers for climate resilience with a focus on fostering better collaboration among actors and initiatives by piecing together the fragmented landscape of existing initiatives and mobilizing investments for sustainable agriculture.

2.1.6 FINANCE FOR FOOD SYSTEMS TRANSFORMATION

Investment cost

The investment costs of not only ending hunger by 2030, but also maintaining agricultural GHG emissions at a level that meets the Paris Agreement are estimated at USD 33 billion per year (Rosegrant, Sulser and Wiebe, 2022; Gaupp, 2022). In the Global South alone, USD 4 billion of investment in international and private research and development is required annually to achieve SDG 2 (Zero Hunger) by 2030. On top of that, reducing and sequestering emissions to ensure less than 2 °C of global warming will require an estimated USD 6.5 billion per year of national and international investment in climate-smart technical mitigation solutions for farming in the Global South, as well as USD 4.7 billion in investment in better water resource management to reduce water demand. What is more, a recent top-down and bottom-up approach taken by the Climate Policy Initiative (CPI) and FAO (2025) estimates the costs needed to transition global food systems to a 1.5 °C pathway at more than USD 1 trillion per year.

[12] For further information please see: https://cop29.az/en/pages/baku-harmoniya-climate-initiative-for-farmers-concept

2.1.7 CLIMATE-RELATED DEVELOPMENT FINANCE FOR AGRIFOOD SYSTEMS

The share of global climate-related development finance flowing to agrifood systems fell from an average of 37 percent in 2000–2010 to an average of 24 percent in 2011—2022. In 2022, climate-related development finance allocations to all sectors reached a record USD 130 billion, of which agrifood systems attracted USD 29 billion. At the same time, however, agrifood systems' share of total climate-related finance was 23 percent, unchanged from the average in 2019–2020 (Galbiati and Bernoux, 2024).

2.2. UPDATE ON GLOBAL CLIMATE STATUS AND KEY SCIENTIFIC FINDINGS SINCE 2019

2.2.1 GREENHOUSE GAS EMISSIONS

COVID-19 pandemic restrictions resulted in a temporary dip in global GHG emissions in 2020—2021. However, emissions have since rebounded, reaching an all-time high of 57.1 $GtCO_2e$ in 2023, an increase of 3.6 percent from 2019 (UNEP, 2024). Net emissions increased for all Kyoto gases, with the largest absolute increase in fossil CO_2 emissions, partially offset by a reduction in CO_2 emissions from land use, land-use change and forestry (LULUCF) (based on bookkeeping models). Note that absolute quantities of aggregate emissions in 2023 are not directly comparable to emissions reported by the IPCC in 2019 or 2022 due to a subsequent revision of estimated CO_2 LULUCF emissions (IPCC, 2019a, 2022).

GHG concentrations also continued to increase, reaching new highs in 2023, with CO_2 at 420 parts per million (ppm), methane (CH_4) at 1 934 parts per billion (ppb) and nitrous oxide (N_2O) at 337 ppb (WMO, 2024). These values are 151 percent, 265 percent and 125 percent of pre-industrial (pre-1750) levels, respectively, corresponding to increases of about 2.4 percent, 2.9 percent and 1.5 percent above concentrations in 2019. CH_4 concentrations saw extraordinarily high growth rates in 2020—2022, attributed to increased microbial activities from wetlands, waste and agriculture (Michel *et al.*, 2024). This is consistent with other studies suggesting tropical wetlands as a key driver of faster emissions growth and a possible indication of climate feedbacks on emissions (Shindell *et al.*, 2024).

2.2.2 TEMPERATURE AND SEA-LEVEL RISE

Alongside GHG emissions, global average surface temperatures have reached new highs in recent years, with unusually large increases in 2023 and 2024. The IPCC (2019a) reported that the decadal average global mean surface temperature from 2006 to 2015 was 0.87 °C (0.75 °C to 0.99 °C) above the 1850—1900 average (5th—95th percentile confidence interval). Using a revised methodology to estimate atmospheric temperature above the oceans, the IPCC's Sixth Assessment Report updated the estimate for the same time period to 0.94 °C (0.79 °C to 1.04 °C) (Gulev *et al.*, 2021). The global average surface temperature has increased further since then, reaching 1.19 °C (1.06 °C to 1.30 °C) in 2014—2023 and 1.43 °C (1.32 °C to 1.53 °C) in 2023 relative to 1850—1900 (Forster *et al.*, 2024).

The majority of global temperature datasets indicate that 2024 was the first calendar year when global average surface temperatures exceeded the 1850—1900 average by at least 1.5 °C (WMO, 2025). However, this does not mean that global warming has reached 1.5 °C, as global warming is generally defined as the average increase in temperature over several decades; the IPCC uses a 20-year period, for instance (IPCC, 2021). These observations, therefore, are consistent with the expectation that global warming of 1.5 °C will be reached by the late 2020s or early 2030s (IPCC, 2021).

Alongside global average surface temperatures, global average sea levels also continue to increase. The global rate of sea-level rise increased to 4.5 millimetres per year (mm/yr) in 2023, more than double the rate of 2.1 mm/yr in 1993 (Hamlington *et al.*, 2024).

2.2.3 REMAINING CARBON BUDGET

The continued rise in global atmospheric temperature and the persistent high level of GHG emissions means that the scope for humanity to keep global warming to 1.5 °C, while still emitting increasing amounts of GHGs, has decreased substantially. This is indicated by the remaining carbon budget, which describes the total amount of CO_2 emissions consistent with limiting global warming to a given level. The remaining carbon budget consistent with keeping global warming to 1.5 °C with a 50 percent probability was estimated at 770 $GtCO_2$ from 1 January 2018 (IPCC, 2018). In other words, the world could emit, at most, 770 $GtCO_2$ from 1 January 2018 onwards and still keep global warming to 1.5 °C with at least a 50—50 chance. This was revised down to 500 $GtCO_2$ from 1 January 2020 (IPCC, 2021) and the latest estimates put the remaining carbon budget from 1 January 2024 at only 200 $GtCO_2$ (Forster *et al.*, 2024). This is less than five years of current global net CO_2 emissions.

Estimates of the remaining carbon budget assume concurrent reductions in non-CO_2 emissions, including about a 50 percent reduction in global CH_4 emissions by 2050 from 2019 levels. Greater or lesser reductions in CH_4 emissions would increase or decrease the remaining carbon budget by about 250 $GtCO_2$ (IPCC, 2018; Canadell *et al.*, 2021; Forster *et al.*, 2024). This suggests that if global CH_4 emissions are not reduced substantially in the near term, the remaining carbon budget for global warming of 1.5 °C will have already been exhausted (Reisinger, 2024; Shindell *et al.*, 2024).

2.2.4 BENCHMARKS OF EMISSION-REDUCTION TARGETS AND OVERSHOOTING 1.5 °C

A large gap remains between the emission reductions necessary to limit global warming to 1.5 °C or less than 2 °C and the emission reductions pledged by countries as part of their NDCs and long-term pledges under the Paris Agreement. Moreover, current policies are insufficient to constrain global emissions to NDC commitments for 2030 (UNEP, 2024).

The most recent UNEP (2024) Emissions Gap Report indicates that, under current policies, global emissions in 2030 will be about 57 $GtCO_2$, on a par with estimated global emissions in 2023, but about 2 $GtCO_2$ and 5 $GtCO_2$ higher than emissions under conditional and unconditional NDCs, respectively. Unconditional elements of NDCs refer to mitigation efforts put forward without any conditions. Conditional elements refer to mitigation efforts that are contingent on international cooperation, such as bilateral and multilateral agreements, financing or monetary and/or technological transfers. Pledged 2030 emissions, based on conditional and unconditional NDCs, remain 11 $GtCO_2$ and 14 $GtCO_2$, respectively, higher than those in cost-effective global emission pathways that limit warming to below 2 °C with at least a 66 percent probability, and 19 $GtCO_2$ and 22 $GtCO_2$ higher than those in global emission pathways that limit warming to 1.5 °C with a 50 percent probability in 2100, but a temporary exceedance of that level (UNEP, 2024).

An increasing number of countries, accounting for more than 80 percent of global emissions, have adopted long-term net-zero targets (UNEP, 2024). However, confidence in the implementation of many of those targets remains low. If all near-term and long-term pledges were met, global warming could be limited to about 1.8 °C by 2100; however, if only those pledges are considered where clear plans and policies exist, global warming could reach 2.4 °C by 2100 (Rogelj *et al.*, 2023). Current policies alone indicate warming of around 3.1 °C (in a range of 1.9 °C to 3.8 °C) by 2100, with temperatures continuing to increase beyond this (UNEP, 2024).

The large emissions gap, insufficiency of current policies and diminished remaining carbon budget now make it virtually impossible to limit global warming to 1.5 °C without exceeding that level at least for several decades (Bustamante *et al.*, 2023; Reisinger and Geden, 2023). A subsequent return to 1.5 °C would rely on sustained global net-negative CO_2 emissions supported by further sustained reductions in CH_4 emissions, both of which face major challenges in terms of feasibility (IPCC, 2023; Reisinger and Geden, 2023; Schleussner *et al.*, 2024). However, increased near-term action and strengthening the credibility of long-term pledges could materially change the amount by which 1.5 °C will be exceeded and the feasibility of a return to 1.5 °C (Schleussner *et al.*, 2024; UNEP, 2024).

2.3. GLOBAL CARBON DIOXIDE FLUXES FROM LAND USE, LAND-USE CHANGE AND FORESTRY

Land plays a significant dual role in the global carbon budget. On the one hand, carbon dioxide (CO_2) fluxes from land use and land-use change are a major source of anthropogenic CO_2 emissions, accounting for around one-third of cumulative CO_2 emissions since 1750 and about 12 percent of current annual emissions, primarily through deforestation (Friedlingstein *et al.*, 2023). On the other hand, terrestrial sinks, especially forests, absorb nearly one-third of total anthropogenic CO_2 emissions (Friedlingstein *et al.*, 2023; Pan *et al.*, 2024). However, the stability of this absorption is increasingly threatened by the impacts of climate change itself (Ke *et al.*, 2024).

The relevance of land use is also underscored in future mitigation potential, as highlighted by both scientific and policy documents. According to the Working Group III contribution to the latest IPCC Assessment Report (Nabuurs *et al.*, 2022), the agriculture, forestry and other land use (AFOLU) sector could provide 20–30 percent of the global GHG emissions mitigation needed to reach 1.5 °C or 2 °C targets by 2050, with the LULUCF sector contributing the largest share. In addition, LULUCF accounts for 25 percent of net emissions reductions pledged by countries in their NDCs (see, for example, Roman-Cuesta, 2024). As climate policy shifts increasingly towards implementing these pledges, there is a growing emphasis on tracking national progress. However, monitoring LULUCF sectoral progress is challenging due to the complexities of accurately measuring land-based GHG emissions and removals, especially the anthropogenic component.

Since the IPCC (2019a) Special Report on Climate Change and Land, important progress has been made on identifying and understanding the reasons for the differences between global models, observations and inventories for estimating the impacts of various land-use practices on carbon, energy and water fluxes (Pongratz *et al.*, 2021). In particular, in recent analyses, global net LULUCF CO_2 flux estimates show divergences of several $GtCO_2$/yr between various approaches (IPCC, 2022). Most of these differences have been explored in the scientific literature, while others remain relatively poorly examined. The difference between two prominent country-based datasets — national GHG inventories (NGHGIs) and FAOSTAT — is largely due to the broader coverage of NGHGIs, which include non-biomass carbon pools and non-forest land uses, as well as differences in data for forest carbon sinks. This difference reflects the fact that FAO's country reporting emphasizes area and biomass, whereas the UNFCCC focus is on carbon fluxes (Grassi *et al.*, 2022).

A striking example of such discrepancy is the 6-7 $GtCO_2$/yr gap between global models from the global carbon budget (bookkeeping models and dynamic global vegetation models) and the NGHGIs. This is primarily attributed to differing definitions of anthropogenic CO_2 emissions and removals in managed forests (Grassi *et al.*, 2018, 2023; Schwingshackl *et al.*, 2022).

National definitions of managed forest areas are broader than those used in global models due to NGHGIs' more inclusive definitions of managed land. Furthermore, indirect human-induced environmental effects — such as increased vegetation growth from atmospheric CO_2, nitrogen deposition and changing climatic factors — are generally classified as non-anthropogenic by global models, but as anthropogenic in NGHGIs. NGHGIs, aligned with IPCC Guidelines (IPCC, 2006, 2019b) and using the "managed land proxy", treat much of the land sink as anthropogenic, whereas global models do not. Especially in regions without active land-use changes (for example, forests that remain intact), observational data from NGHGIs, such as forest inventories, do not allow the separation of direct and indirect human impacts (IPCC, 2019b). This is the approach required by parties to the Paris Agreement under the Enhanced Transparency Framework.

Notably, there is no universally superior method, as each has unique purposes and constraints. The largely distinct scientific communities informing the IPCC Inventory Guidelines (used in NGHGIs) and the IPCC Assessment Reports (used in global models) have developed methods tailored to their needs. While both approaches are valid within their respective contexts, their results are not directly comparable.

This lack of comparability is problematic: global models underpin LULUCF estimates in IPCC Assessment Reports, both historically (through bookkeeping models) and in future emissions scenarios (through integrated assessment models, or IAMs). Meanwhile, NGHGIs form the basis for evaluating national compliance with climate commitments and collective progress against IAM-based benchmarks under the Paris Agreement's Global Stocktake mechanism. This lack of comparability is further complicated by the large uncertainty over emerging climate-induced shifts in the terrestrial carbon budget (Ke *et al.*, 2024), which may alter land-based mitigation potential and compliance with country targets.

To address this disparity, two-way "translation" between the approaches is essential. Significant progress towards this goal has been achieved (Grassi *et al.*, 2023; Schwingshackl *et al.*, 2023; Gidden *et al.*, 2023; Friedlingstein *et al.*, 2023), but further work is required. This reconciliation affects estimated global carbon budgets and net-zero timelines (IPCC, 2023), underscoring the need to communicate these nuances effectively.

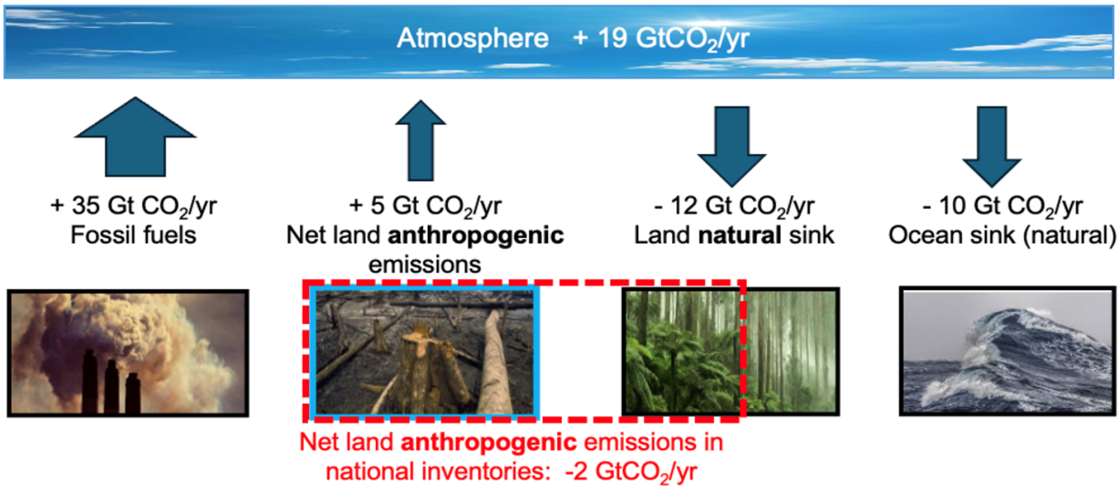
One notable area of difference (illustrated in **Figure 2.2**) is the relatively limited exploration of earth observation (EO) data compared with NGHGIs. EO data, when combined with ground data and models, will play a pivotal role in enhancing the accuracy of national reporting and verification under the Paris Agreement (Melo *et al.*, 2023; Heinrich *et al.*, 2023). It may also serve as a benchmark for land-sink estimates from global models. An emerging role will also be played by EO-based estimates of biomass stock changes and by inverse modelling (Xu *et al.*, 2021; Deng *et al.*, 2021).

In summary, despite the growing number of studies, building on the increasing modelling capabilities and monitoring opportunities offered by new observation tools, large inconsistencies in LULUCF CO_2 flux estimates remain on the global, regional and national scale. These differences present significant obstacles to accurately assessing collective climate progress and confidence in land-based mitigation options. However, evidence suggests that these discrepancies are surmountable with cooperation across key communities — global carbon modellers, EO experts and NGHGIs.

To advance this goal, a recent IPCC Expert Meeting gathered experts from these communities to foster shared understanding, enhance collaboration and create a roadmap to address these challenges (IPCC, 2024). The Expert Meeting outlined several strategic actions, focusing on targeted improvements within each community and strengthening cross-community collaboration. There is strong interest in deepening dialogue across communities and building mutual confidence in land-use CO_2 flux estimates over the coming years. Achieving this will involve expanding data and information exchange, further developing platforms for dataset comparison (for example, the "global land use carbon fluxes" hub) (EU Observatory on Deforestation and Forest Degradation, 2024), establishing joint protocols for data translation, and involving regional and national experts from diverse communities as part of a mutual learning initiative — potentially coordinated by the Global Carbon Project.

Initial results from these efforts are expected within three to four years, to be reflected in the IPCC's Seventh Assessment Report, countries' Biennial Transparency Reports and the Second Global Stocktake. Establishing an operational approach for translating global model results into national inventory definitions would help bridge the gap between the IPCC Assessment Reports' land-use estimates and scenarios (based on global models) and the mitigation processes under the Paris Agreement, which rely on NGHGI data. This approach will also enhance confidence in land use as a viable mitigation strategy and strengthen the data and science supporting the Global Stocktake process.

FIGURE 2.2.The global carbon budget (2013—2022)



Note: Sources and sinks of anthropogenic emissions (Global Carbon Project, 2024), showing the different system boundaries of net land anthropogenic emissions by global models (blue box) and national inventories (red box). Numbers are from Friedlingstein *et al.* (2023), excluding the "budget imbalance" required to make all numbers sum to zero.

Sources: Global Carbon Project. n.d. The Global Carbon Project. Canberra. [Cited 24 October 2024]. https://www.globalcarbonproject.org/; Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Bakker, D.C.E, Hauck, J., *et al.* 2023. Global Carbon Budget 2023, Earth System Science Data, 15: 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

2.4. GLOBAL GREENHOUSE GAS, NITROUS OXIDE AND METHANE BUDGET IN AGRIFOOD SYSTEMS

Methane (CH_4) and nitrous oxide (N_2O) are the second- and third-most important GHGs after CO_2. Though emitted in smaller quantities, they have much higher global warming potential (GWP). Over a 100-year time horizon, N_2O is 273 times and CH_4 is 28 times more potent than CO_2. However, over a 20-year time horizon, CH_4 is 81 times more powerful than CO_2. CH_4 has a short atmospheric lifetime (around nine years), making its reduction critical for immediate cooling benefits. In contrast, N_2O persists for over 100 years, requiring long-term efforts to mitigate it (Smith *et al.*, 2021). These gases also have additional environmental impacts. CH_4 contributes to tropospheric ozone formation, harming ecosystems and human health. N_2O depletes the stratospheric ozone layer, slowing the recovery of the ozone hole.

Therefore, quantifying the global budgets of CH_4 and N_2O is essential to identifying key emission sources, understanding trends and developing targeted mitigation strategies. Agriculture, a major contributor to both CH_4 and N_2O emissions, requires precise emission data to inform best practices such as optimized fertilizer use, livestock management and better rice cultivation techniques. Without reliable data, mitigation efforts may fall short of achieving meaningful emission reductions. In this section, we provide an overview of global CH_4 and N_2O emissions in agrifood systems based on the most recent reports on the global CH_4 (Saunois *et al.*, 2024) and N_2O budgets (Tian *et al.*, 2024), which synthesize the most up-to-date estimates for non-CO_2 GHGs since 2019.

2.4.1 METHANE EMISSIONS AND TRENDS: ATMOSPHERIC LEVELS AND AGRICULTURAL CONTRIBUTIONS

Globally averaged surface concentrations of CH_4 reached 1 934 ppb in 2023 (WMO, 2024), up 265 percent relative to pre-industrial concentrations. Between 2000 and 2023, atmospheric CH_4 concentrations increased by 149 ppb, up 8 percent from 2000 levels. The annual atmospheric CH_4 growth rate increased from 6.1 million tonnes per year (Mt/yr) during the 2000s to 20.9 Mt/yr in the 2010s. Growth has accelerated further over the past three years (2020—2023), with annual growth rates higher than any observed since 1986 (the year when continuous measurement started). This has led to an accumulation of 41.8 Mt of CH_4 in 2020, twice that of the past decade.

Direct anthropogenic CH_4 sources include emissions for fossil-fuel exploitation and use, agriculture, waste handling, and biomass and biofuel burning, which account for around 60 percent of total CH_4 emissions (Saunois *et al.*, 2024). Agriculture (livestock and rice paddies) is the main anthropogenic source. accounting for 40 percent of global anthropogenic emissions. For the 2010s, total CH_4 emissions from agriculture are estimated at 144 (132—155) Mt/yr of CH_4 (**Table 2.5**). Emissions from ruminants and manure accounted for an estimated 78 percent of agricultural emissions, while emissions from rice cultivation were an estimated 22 percent. Decomposing agricultural waste can generate small but notable amounts of CH_4 in poorly managed systems.

Between 2000 and 2020, agricultural CH_4 emissions increased 14 percent, driven mainly by rising livestock numbers and manure production (+17 Mt/yr). Emissions from rice cultivation increased by 3 Mt/yr of CH_4, or 10 percent from 2000—2020. Africa, Brazil, Central America, South Asia and Southeast Asia saw the largest increases in agricultural emissions (Jackson *et al.*, 2024; Saunois *et al.*, 2024).

2.4.2 NITROUS OXIDE EMISSIONS AND TRENDS: ATMOSPHERIC LEVELS AND AGRICULTURAL CONTRIBUTIONS

Globally averaged surface concentrations of N_2O have also risen significantly, reaching 337 ppb in 2023, up 125 percent on pre-industrial concentrations (WMO, 2024). N_2O emissions have accelerated in recent years, with growth rates from 2020 to 2022 at their highest levels since 1980, when reliable measurements began, and about 30 percent higher than in the past decade (2010 – 2019).

According to the most recent report (Tian *et al.*, 2024), agriculture is responsible for about 75 percent of anthropogenic N_2O emissions. These emissions occur through direct soil emissions and indirect pathways, such as runoff and leaching. Direct emissions arise from nitrogen applied directly to agricultural land through synthetic fertilizers, manure and other organic amendments. These emissions result from the biological processes of nitrification and denitrification in soils, releasing N_2O into the atmosphere.

In the 2010s, direct agricultural emissions contributed about 5.7 Mt/yr of N_2O, accounting for 56 percent of total anthropogenic N_2O emissions. Key sources include direct soil emissions (3.1 Mt/yr of N_2O), manure left on pasture (2.0 Mt/yr), manure management (0.5 Mt/yr) and aquaculture activities (0.2 Mt/yr). Indirect agricultural emissions accounted for 17 percent of total anthropogenic N_2O emissions, with an average of 1.7 Mt/yr. The primary sources include nitrogen deposition on land (1.1 Mt/yr of N_2O) and inland waters, estuaries and coastal waters (0.6 Mt/yr).

From 2000 to 2020, total direct agricultural emissions increased 31 percent, from 6.1 Mt/yr N_2O in 2000 to 8.0 Mt/yr in 2020 (**Table 2.5**). Specifically, direct soil emissions rose from 2.4 Mt/yr to 3.3 Mt/yr over the same period, driven by the increasing use of synthetic fertilizers. Emissions from manure left on pasture increased from 1.7 Mt/yr to 2.2 Mt/yr of N_2O, reflecting the growth in global livestock populations. Manure management emissions showed a smaller rise, from 0.4 Mt/yr to 0.5 Mt/yr. Aquaculture emissions increased significantly, from 0.1 Mt/yr to 0.2 Mt/yr of N_2O, driven by the expansion of fish farming, particularly in China. Indirect emissions increased 27 percent from 1.5 Mt/yr N_2O in 2000 to 1.9 Mt/yr in 2020, reflecting an increase in land-based nitrogen deposition, as well as the impact of increased nitrogen runoff from agricultural fields.

Direct nitrogen additions in agriculture are the main cause of the increase in agricultural emissions. Developing countries in Africa, South America, and South and Southeast Asia show a significant increase in nitrogen fertilizer use. Among them, Ethiopia and Pakistan have grown N_2O emissions by more than 200 percent in the past 40 years, from 1980-2020. However, anthropogenic N_2O emissions in China have been declining since 2016, because the country has reduced its use of nitrogen fertilizer by about 5 Mt, from its peak of 31 Mt in 2015 to 26 Mt in 2020.

2.4.3 IMPLICATIONS AND PATHWAYS FOR NET-ZERO EMISSIONS

Atmospheric concentrations of CH_4 and N_2O have risen sharply over the past decade, exceeding the most pessimistic emission scenarios projected by the IPCC. These trends indicate a risk of global temperatures increasing by more than 3 °C by the end of the century if current emissions remain unchecked. Agriculture plays a significant role in these emissions, accounting for around 50 percent of global CH_4 emissions and 75 percent of N_2O emissions.

To achieve the goal of the Paris Agreement, which aims to limit global warming to below 2 °C, the IPCC Working Group III has outlined ambitious reduction targets for these gases by 2050. These include a 45 percent reduction in CH_4 emissions and a 20 percent reduction in N_2O emissions from 2019 levels (IPCC, 2022a). By prioritizing reductions in CH_4 and N_2O emissions, the agricultural sector can play a pivotal role in stabilizing the climate while supporting sustainable food production.

Key agricultural mitigation measures for non-CO_4 emissions include reducing enteric fermentation (CH_4: 0.1–1.2 $GtCO_2e$/yr), improving rice cultivation (CH_4: 0.1–0.9 $GtCO_2e$/yr) and managing cropland nutrients (N_2O: 0.03–0.7 $GtCO_2e$/yr) (Roe *et al.*, 2019). A recently updated study indicated that IAMs are estimating a higher cost-effective mitigation potential of 2.7 $GtCO_2e$/yr by 2050 (33 percent of land-based potential) compared with sectoral estimates (0.6 ± 0.2 $GtCO_2e$/yr). This gap arises from differences in baseline emissions, assumptions about mitigation technology adoption and IAMs' inclusion of economic dynamics (Roe *et al.*, 2021).

TABLE 2.5. Global nitrous oxide and methane budgets in agrifood systems

N_2O emissions (Mt/yr)	2000			2010-2019			2020			increase	increase (%)
	mean	min.	max.	mean	min.	max.	mean	min.	max.		(2000-2020)
Direct soil emissions	2.4	2.1	2.8	3.1	2.5	3.8	3.3	2.7	4.1	0.9	38
Manure left on pasture	1.7	1.1	2.3	2.0	1.3	2.8	2.2	1.4	3.0	0.5	29
Manure management	0.4	0.4	0.4	0.4	0.3	0.5	0.5	0.3	0.5	0.1	25
Aquaculture	0.1	0.0	0.2	0.2	0.0	0.5	0.2	0.0	0.5	0.1	100
Indirect emissions	1.5	1.1	1.8	1.7	1.1	2.1	1.8	1.1	2.3	0.3	20
Total ag.N_2O emissions	**6.1**	**4.7**	**7.6**	**7.4**	**5.2**	**9.6**	**8.0**	**5.5**	**10.3**	**1.9**	**31**
GWP-100	1665	1270	2066	2020	1415	2631	2184	1502	2816	519	
CH_4 emissions (Mt/yr)	**2000-2002**			**2010-2019**			**2020**				
Enteric fermentation and manure mgt.	100	95	107	112	107	118	117	114	124	17	17
Rice cultivation	29	23	33	32	25	37	32	29	37	3	10
Total ag. CH_4 emissions	**129**	**118**	**140**	**144**	**132**	**155**	**147**	**143**	**149**	**18**	**14**
GPW -100	3612	3304	3920	4032	3696	4340	4116	4004	4172	504	14
GWP -20	10475	9582	11368	11693	10718	12586	11936	11612	12099	1462	14

Source: Table compiled for this publication using data from: Tian *et al.* 2024 (for N_2O) and Saunois *et al.* 2024 (for CH_4)

2.5. FARMING PRACTICES AND THEIR IMPACTS: AN OUTCOME-BASED APPROACH TO CLIMATE TARGETS AND NATURE REGENERATION

Global food security is under increasing pressure from population growth, changing diets and the growing negative impact of climate change. To maintain a high level of food security while reducing the negative environmental impact of agriculture, it is crucial to identify sustainable farming practices capable of achieving high productivity, environmental protection, and climate change mitigation and adaptation.

2.5.1 WHAT EVIDENCE IS AVAILABLE TO ASSESS THE SUSTAINABILITY OF AGRICULTURE?

Scientists have conducted a lot of research into how different farming practices affect the environment and climate, as well as how they affect agricultural productivity. However, the results of individual experiments are often contradictory and suffer from a lack of statistical power to support clear conclusions. Meta-analysis, a powerful statistical tool, is increasingly being used as a solution to synthesize evidence from multiple studies and provide a more comprehensive and robust assessment of farming practices. By integrating results from diverse contexts, meta-analyses enhance statistical power and provide more reliable conclusions about the impacts of various practices. They also help in understanding and quantifying the variability of these impacts, while identifying the most relevant influential factors (such as pedo-climatic conditions and type of land management) (Makowski *et al.*, 2023).

Recognizing the need for a comprehensive and accessible resource, the European Commission Joint Research Centre, together with collaborators from other institutions, developed the JRC-Farming practices evidence library (Schievano *et al.*, 2024). Through a systematic screening of more than 14 000 records of peer-reviewed papers (reporting either meta-analysis or quantitative systematic review), this dataset summarizes 570 meta-analysis papers reporting on the effects of a wide range of farming practices (including different agronomic techniques, cropping systems, livestock and landscape management options) over 34 impact categories, targeting sustainability outcomes related to environment, climate and productivity. The library is accessible via an online tool that has three main functions[13]:

- **to facilitate knowledge synthesis** by providing researchers with a unique platform where they can access and synthesize existing knowledge and, furthermore, foster collaboration and accelerate progress in sustainable agriculture research;
- **to support decision-making processes** by helping to identify farming practices with strong evidence of positive impacts across multiple sustainability objectives; and
- **to identify knowledge gaps** by highlighting areas where research is lacking, in turn guiding future research to address critical uncertainties.

2.5.2 WHICH SUSTAINABLE AGRICULTURAL PRACTICES CAN HELP REGENERATE ECOSYSTEMS?

In the JRC-FP Evidence Library, seven main sustainability outcomes were mapped from existing evidence, each including one or more impact categories, as shown in **Table 2.6**. Each impact category includes several different types of metric, widely used for on-field measurements in experimental trials or in modelling (for example, life-cycle assessments, or LCAs).

[13] Find the tool at: https://datam.jrc.ec.europa.eu/datam/mashup/JRC_FP_EVIDENCE_LIBRARY/

TABLE 2.6. Classification of farming practice outcomes towards sustainability and ecosystem regeneration

Sustainability outcomes	Impact categories	Number of specific metrics or indicators retrieved from 570 meta-analyses (JRC-FP library)
Biodiversity	Biodiversity	105
	Pests, diseases, weeds and natural enemies	36
	Pollination	21
Carbon sequestration	Carbon sequestration (for example, soil C-contents/ stocks/sequestration rates, woody biomass-C or pyrogenic-C)	46
GHG mitigation	GHG emissions (CH_4, N_2O emissions from soil and livestock)	21
	GWP (LCA)	1
Pollution and antimicrobials	Acidification (LCA)	2
	Air pollutant emissions (such as ammonia)	4
	Antimicrobial resistance	1
	Ecotoxicity (LCA)	1
	Eutrophication (LCA)	2
	Heavy metals pollution	23
	Nutrient leaching and run-off	23
	Odour emissions	1
	Pesticide use	3
	Plastic residues	1
	Water quality	14

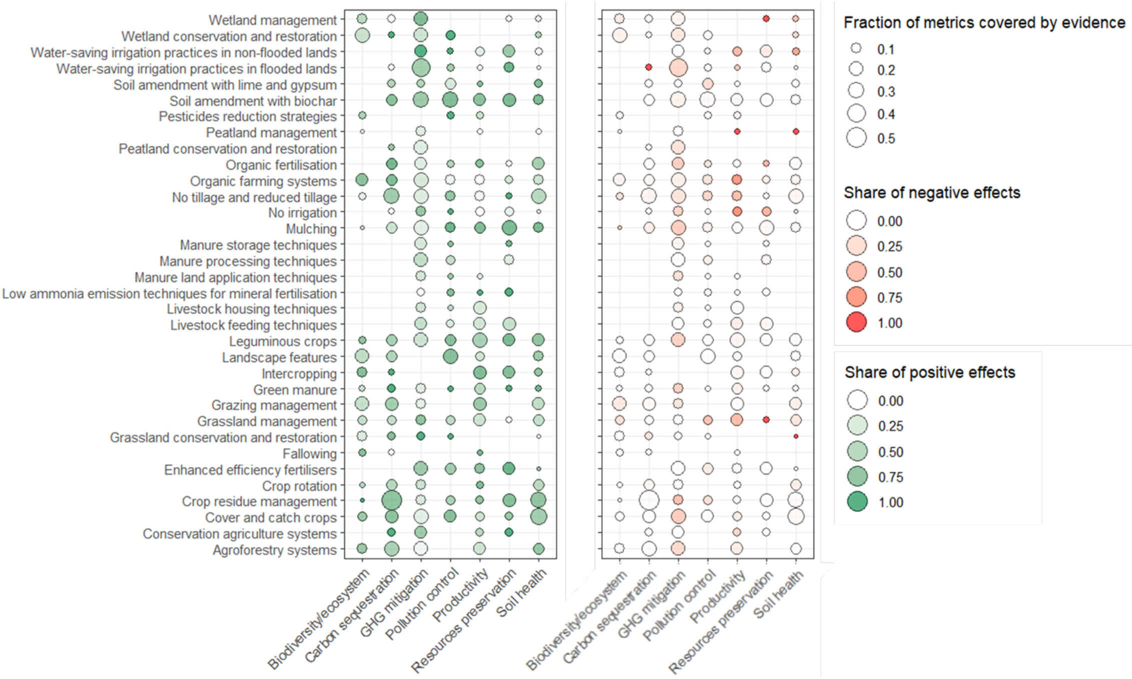
Sustainability outcomes	Impact categories	Number of specific metrics or indicators retrieved from 570 meta-analyses (JRC-FP library)
Productivity	Animal production	16
	Crop yield	32
	Grassland production	14
Sustainable use of resources	Nitrogen footprint (LCA)	2
	Energy use (LCA)	2
	Land use (LCA)	1
	Nutrient excretion	6
	Nutrient recovery	2
	Plant nutrient uptake	17
	Resource depletion (LCA)	1
	Water footprint (LCA)	4
	Water use	7
Soil health	Soil biological quality	72
	Soil erosion	15
	Soil nutrients	27
	Soil physico-chemical quality	28
	Soil water retention	23

Source: Schievano, A., Pérez-Soba, M., Bosco, S., Montero-Castaño, A., Catarino, R., Chen, M., *et al.* 2024. Evidence library of meta-analytical literature assessing the sustainability of agriculture – a dataset. Scientific Data, 11(1): 979. https://doi.org/10.1038/s41597-024-03682-6

Figure 2.3 presents an overview of the potential effects of 34 farming practice categories on the aforementioned sustainability outcomes. The results within each category may include several different types of practice, while each outcome includes different impacts, as quantified by different metrics. "Positive" or "negative" effects are determined using available meta-analytical evidence. A colour scale is used to account for the outcomes with a higher share of results reporting a positive effect (in green) and potential trade-offs (in red). The size of the bubbles represents how broad the available evidence is across the different metrics used to quantify outcomes (share of metrics covered by results over the total number of metrics).

Figure 2.3 shows several important results concerning the impacts of farming practices:

FIGURE 2.3. Synthesis of the evidence across categories of farming practice and sustainability outcomes



Note: The scientific evidence collected in the JRC-FP library (version 2024) includes meta-analyses published up to 2023.

Source: Schievano, A., Pérez-Soba, M., Bosco, S., Montero-Castaño, A., Catarino, R., Chen, M., *et al.* 2024. Evidence library of meta-analytical literature assessing the sustainability of agriculture – a dataset. Scientific Data, 11(1): 979. https://doi.org/10.1038/s41597-024-03682-6

- **Biodiversity**: Positive impacts are predominantly associated with farming practice categories that focus on landscape and cropping-system diversification and rotation, soil cover, the substitution of pesticides and conservation or restoration. Examples include: legume crop rotation, cover crops, intercropping, agroforestry and organic farming. However, around half of farming practice categories remain uncovered by results or covered only on a narrow spectrum of metrics (see bubble size in **Figure 2.3**). The lack of evidence for some practices may hide potential trade-offs. For instance, the effects on biodiversity and soil biological quality remain unexplored for practices such as the use of nitrification inhibitors or urease inhibitors (in the "enhanced-efficiency fertilizers" category); such biocides target specific soil microbes, but may have unintended effects on other organisms (Chen *et al.*, 2023).
- **Carbon sequestration:** Farming practices that minimize soil disturbance, promote amendment and organic fertilization, and introduce woody biomass show mainly positive impacts. These include cover crops, agroforestry and organic amendments. Only water-saving practices in flooded land (in particular, draining rice paddy fields) negatively affect soil carbon stocks. Other categories show less clear-cut results, such as no tillage, which was found to potentially increase carbon sequestration, but with variable efficiency depending on other associated practices, different soil horizons or types of soil, and so on. Knowledge gaps are typically associated with farming practice categories not directly related to carbon sequestration (such as livestock feeding and manure storage techniques).
- **GHG mitigation:** Some farming practice categories (such as agroforestry, crop rotation, and grassland, wetland or peatland management) consistently show potential for GHG mitigation. The large majority (including all practices dealing with livestock and manure

management) show contrasting results; in other words, the effect depends strongly on the specific practice, metric or pedo-climatic conditions. This highlights the complexity of GHG mitigation and the need for context-specific assessments and recommendations. In addition, the large majority of meta-analyses do not consider quantitative assessments that integrate different GHG emissions and carbon stocks.

- **Soil health:** Around half of the farming practice categories show positive effects on impacts related to soil health. However, the range of impacts studied is often limited. For example, the potential trade-offs in soil biological quality are not assessed for enhanced-efficiency fertilizer use (such as nitrification/urease inhibitors, which are function-targeted biocides). Other categories show potential negative effects (for example, the use of treated wastewater as an irrigation source tends to increase soil salinity, while the abandonment of cropland and conversion to grassland leads to a decrease in soil phosphorous stocks). Knowledge gaps exist in relation to some practice categories, such as manure processing techniques, fallowing, wetland management and peatland conservation.

- **Productivity:** Several farming practice categories (such as the use of leguminous crops, rotation, crop residue retention and some landscape features) show positive effects on productivity and other outcomes, while several report contrasting results (where productivity might be either increased or decreased depending on the context) or, sometimes, potential trade-offs. For instance, organic farming systems are reported to decrease crop yields. In most cases, however, productivity is measured using narrow ranges of impact indicators (for example, crop yield based on weight, not including nutritional values). Also, only a few assessments consider whole-farm productivity, rather than single-crop yield at field or plot scale. Crop-yield stability over time after implementation of the farming practice is also rarely considered.

- **Pollution control:** Several farming practice categories show potential for effective pollution control (as plastic mulching, for instance, generates large amounts of plastic residues, the use of amendments in grasslands potentially leads to nutrients losses, and soil amendment with biochar, when associated with urea- or ammonium-rich mineral fertilization, can facilitate ammonia emission). Considering the impact categories contributing to pollution control, the share covered by evidence is less than 30 percent for most farming practice categories. This is partially due to the relatively high number of impacts (11), all of which may not always be relevant, depending on the practice assessed. In contrast, some existing knowledge gaps may be highly relevant. For instance, for organic fertilization (for example, using compost, manure or sewage sludge), assessment of the impacts of heavy-metal pollution or antimicrobial resistance is missing.

- **Resource preservation:** Positive impacts are delivered by farming practices in the categories of organic agriculture, no/reduced tillage, crop diversification (such as cover crops, the use of leguminous crops and agroforestry) and water-saving practices (Bosco *et al.*, 2024). Some potential negative effects emerge, however, for some water-saving irrigation practices (for example, reduced/deficit irrigation leading to decreasing nitrogen-use efficiency or water productivity) and organic fertilization (for example, a lower nitrogen utilization efficiency of manure compared with mineral fertilizers). However, in general, a high share of metrics remains uncovered by results for relevant farming practice categories (such as pesticide reduction strategies, landscape features and agroforestry).

For a detailed assessment that includes specific metrics and indicators, as well as agroecosystem and pedo-climatic contexts, the JRC-FP Evidence Library provides a tool that enables users to browse, select and synthesize specific subgroups and combinations of variables[14].

[14] The tool can be found at: https://datam.jrc.ec.europa.eu/datam/mashup/JRC_FP_EVIDENCE_LIBRARY/

2.5.3 RECOMMENDATIONS FOR STRENGTHENING THE EVIDENCE AND PROMOTING SUSTAINABLE AGRICULTURE

- The impacts of farming practices are highly context specific and require careful consideration of the local conditions of agroecosystems.
- While many practices show positive effects on multiple sustainability outcomes, negative effects can occur. In practice-based policy and incentive frameworks, such as the European Union's Common Agricultural Policy, policymakers need to consider these potential trade-offs carefully.
- Knowledge gaps remain, particularly as regards biodiversity, farm-scale productivity, pollution control and resource preservation. In addition, a current limitation of the JRC-FP Evidence Library is its lack of sufficient evidence on the combined and synergistic effects of several farming practices or more diversified farming systems (such as conservation agriculture, agroecology and regenerative agriculture).
- The transition to sustainable agriculture requires evidence-based decision-making. Continued research and synthesis in this field is crucial. By embracing more comprehensive assessments of the nexus between different outcomes, improving transparency and promoting data sharing, the scientific community can play a vital role in informing the development and implementation of policies and practices that secure a sustainable and resilient future for agriculture.
- The JRC-FP Evidence Library, with its wide collection of synthesized knowledge, is a valuable resource for researchers, policymakers and all stakeholders invested in shaping a more sustainable future for agricultural production.

2.6. THE ROLE OF COASTAL ECOSYSTEMS IN MITIGATION AND ADAPTATION – PROVISION OF CO-BENEFITS

Coastal wetlands such as mangroves, tidal marshes, seagrass and supratidal ecosystems have been highlighted for their importance in sequestering organic carbon — often referred to as "blue carbon" — in their biomass and soils. High rates of carbon accumulation occur in many coastal wetlands due to their high productivity, sediment accumulation and low rates of soil organic matter decomposition in their inundated soils. Although carbon benefits have stimulated efforts to conserve and restore coastal wetlands, their role in climate adaptation has received less attention. Coastal wetlands provide many other ecosystem services and functions to coastal communities and are considered important nature-based solutions (Lovelock *et al.*, 2024). For example, coastal wetlands provide protection for millions of people in coastal zones that are increasingly threatened by greater frequency and severity of cyclones, storm surge and sea-level rise (Costanza *et al.*, 2021). Coastal wetlands also support healthy fisheries and provide habitat for biodiversity (Sievers *et al.*, 2019), improve water quality and are important for livelihoods and culture (Basyuni *et al.*, 2022).

2.7. GLOBAL STATUS OF WATER—FOOD—ENERGY NEXUS AGRICULTURE

The concept of "nexus thinking" has emerged as a framework for governing the interconnected use of natural resources — specifically water, energy and food — and addressing global security issues related to these resources and biodiversity. This approach contrasts with an item-by-item consideration, which misses positive and negative trade-offs, so that the overall assessment is not a linear summation of the various elements.

The way to address the various impacts of human production on the global environment (assessing both the needs of the environment to sustain production and the consequences of production on environmental health and, thus, its capacity and productivity) has also been conceptualized as "planetary boundaries", where rather than assessing anthropogenic perturbations of the global environment as separate concerns (such as climate change, biodiversity loss or pollution), issues are presented simultaneously within nine main boundaries (Richardson *et al.* 2023)[15,16].

However, despite its potential, there is no universally accepted definition or framework for the nexus approach, as it can vary in focus (for example, on land, water, food, biodiversity or energy) (Brouwer *et al.*, 2024). Key challenges to the implementation of the nexus approach include cross-disciplinary collaboration, political and institutional barriers, and the complexity of resource interdependencies. Nevertheless, integrated solutions are crucial to improving outcomes across the nexus, as single-sector policies often create trade-offs with other targets.

To successfully implement nexus strategies, coordination across sectors and recognition of the finite nature of resources are essential. Overall, a nexus approach can enhance sustainability and resilience in managing water, energy and food systems amid global environmental change, thereby enhancing synergies and reducing trade-offs. Estimates show that by 2030, food, water and energy demands will increase by 50 percent, 30 percent and 40 percent, respectively, resulting in increasing GHG emissions, environmental pollution and climate change. Consequently, countries need to adopt policies to sustain renewable resources and find alternative ways to use resources more efficiently (IPCC, 2019a, 2021, 2022a, 2022b).

FAO is exploring the interconnected water–energy–food nexus to enhance global food security and promote sustainable agriculture, especially as demand rises due to population growth, urbanization and changing diets. Agriculture is the largest user of freshwater and consumes over a quarter of global energy for food production. In addition, a significant increase in food production is necessary to feed a projected 9 billion people by 2050 (FAO, n.d.). To address this, FAO has developed a conceptual framework that recognizes the competing interests for limited resources while prioritizing ecosystem integrity. FAO's strategy includes four key areas: providing evidence, developing scenarios, designing response options and facilitating multistakeholder dialogue. It collaborates accordingly with organizations such as the United Nations Economic Commission for Europe on transboundary nexus assessments. This involves evaluating resource governance and interconnections across sectors in shared watersheds. Promoting responsible solar irrigation to mitigate groundwater depletion, ensuring policies to encourage sustainable practices, in addition to tackling food losses and waste, are critical, as these represent significant inefficiencies in resource use and contribute to environmental degradation[17].

[15] However impacts do not sum up linearly, so the aggregate effect won't be understood by such non-interdependent analysis.

[16] The planetary boundaries framework delineates the biophysical and biochemical systems and processes known to regulate the state of the planet within ranges that are historically known and scientifically likely to maintain Earth system stability and life-support systems conducive to human welfare and societal development experienced during the Holocene. Source: https://www.stockholmresilience.org/research/planetary-boundaries.html

[17] Strategies to reduce food waste include improving agricultural practices, enhancing infrastructure, and promoting recycling and recovery methods

FIGURE 2.4. The nexus footprint of an average meal

Source: FAO, 2014. The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture @ https://openknowledge.fao.org/server/api/core/bitstreams/86fe97cc-4a38-4511-a37f-8eb8ea8fe941/content (accessed 15/05/2025)

Overall, FAO's initiatives aim to harmonize the water–energy–food nexus to secure resources sustainably while addressing the challenges posed by climate change and population pressures. In so doing, a nexus minimizes trade-offs, enhances synergies, avoids conflicts amid multiple uses of a resource and builds more options for economic development in a sustainable way.

Many nexus modelling approaches have been published recently (Li *et al.*, 2021a, 2021b; Qiong and Ping, 2021; Peña-Torres, Boix and Montastruc, 2022; Tian *et al.*, 2018). Li *et al.* (2021a) explore the integration of the water—energy—food nexus with circular bioeconomy principles to promote sustainable agriculture. Li *et al.* (2021b) further develop the water—energy—food nexus, incorporating both physical and social processes and highlighting the importance of considering human responses in managing the nexus for sustainable development. Qiong and Ping (2021), considering both water and carbon footprints under uncertainty, propose another model for managing the agricultural water—energy—food—environment nexus to optimize resource use in agricultural practices. Lastly, Peña-Torres, Boix and Montastruc (2002), in a review, summarize various methods and highlight the importance of integrated management strategies to address the challenges posed by climate change and population growth.

Worldwide, some 72 percent of all freshwater withdrawals are used for agriculture, 16 percent are used by industry and 12 percent by municipalities (UN-Water, 2023). Groundwater supplies about 25 percent of all water used for irrigation and half of the freshwater drawn for domestic purposes (UN-Water, n.d.).

From 2015 to 2021, water-use efficiency increased by 20 percent globally. However, 58 percent of reporting countries still boast low water-use efficiency, primarily those with economies that depend largely on agriculture (UN-Water, 2024a). Rising water stress affects food security and biodiversity. There are rapid changes in surface water in one-fifth of river basins (UN-Water, 2021). Around 7—8 percent of the energy generated globally is used for the production and distribution of drinking water (Sharif *et al.*, 2019).

While more than 700 million people are currently hungry (around 733 million people, or 9 percent of the global population in 2023), by 2050, global food production will need to increase by 50 percent to feed the more than 9 billion people projected to live on our planet (FAO, IFAD, UNICEF, WFP and WHO, 2017). Water-harvesting and water conservation techniques could boost rainfed kilocalorie production by up to 24 percent or, if combined with irrigation expansion, by more than 40 percent (FAO, 2020). In sub-Saharan Africa, the area under irrigation is expected to more than double by 2050, benefiting millions of small-scale farmers. However, it has been estimated that 41 percent of current global irrigation water use occurs at the expense of environmental flow requirements (FAO, 2020).

Global water demand is projected to increase by 20—30 percent by 2050 (UN-Water, 2018).

In 2022, some 72 percent of global power generation is water intensive (elaboration from IEA data[18]) (IEA 2012). Power-plant cooling is responsible for 43 percent of total freshwater withdrawals in Europe (more than 50 percent in several countries) and nearly 50 percent in the United States of America (WWAP, 2014). By 2035, water withdrawals for energy production could increase by 20 percent and consumption by 85 percent, driven by a shift towards higher-efficiency power plants with more advanced cooling systems (that reduce water withdrawals but increase consumption) and increased production of biofuel (IEA, 2012). However, there is great uncertainty surrounding the water demand associated with decarbonization in the energy sector, with lower GHG emissions not necessarily being synonymous with lower water demand (Terrapon-Pfaff *et al.*, 2020). Around 30 percent of global energy consumption stems from the agriculture and food sectors (FAO, 2017). A shift towards non-water-intensive renewable sources of energy, such as wind and solar, would bring about a significant reduction of water use per unit of energy produced.

Most of the water used in agriculture is for irrigation. By 2050, food demand will increase by 60 percent, and this will require more arable land and an intensification of production (UN-Water, 2018). This, in turn, will translate into greater use of water for agriculture and potentially increased energy use (and associated GHG emissions) from the expansion of irrigation (Qin *et al.*, 2024).

Recognition of the nexus approach is increasing in both the science and policy areas. Research is expanding the application of the water—food—energy nexus to other areas. For instance, Javan *et al.* (2024) wrote a review of 1 046 peer-reviewed articles on the water—food—energy nexus published between 2015 and 2023, to apply the nexus to a study of urban pollution. More recently, the nexus has been expanded to include the circular bioeconomy (Ansari *et al.*, 2023; Osman *et al.*, 2022).

[18] This sums up data on oil, coal, gas, nuclear and waste share of electricity generation (from www.iea.org/world/energy-mix)

In terms of policy use, both the European Commission Joint Research Centre (2019) and the European Union, United Nations Educational, Scientific and Cultural Organization (UNESCO) and IWA Publishing (2021) focus on an extended nexus approach that includes ecosystems. The water—energy—food—ecosystem nexus (WEFE nexus) approach highlights the interdependence of water, energy, food security and ecosystems (water, soil and land), all of which underpin food security[19]. It identifies mutually beneficial responses based on understanding the synergies of water, energy and agricultural policies. The WEFE nexus also provides an informed and transparent framework for determining the appropriate trade-offs and synergies for maintaining the integrity and sustainability of ecosystems. The European Union, together with the Government of Germany, is supporting the Nexus Regional Dialogues Programme[20], with the aim of enhancing the governance of resources to improve the quality of products while protecting ecosystems from disruptive impacts and minimizing other trade-offs, thus supporting sustainable development.

In addition, under the UNFCCC, since COP23, with first the Koronivia Joint Work on Agriculture and its follow-up, the Sharm el-Sheikh Joint Work on Implementation of Climate Action on Agriculture and Food Security, the need for holistic approaches is gaining recognition. Recently, at COP28, countries agreed a roadmap, including a workshop at the June 2025 session on "Systemic and holistic approaches to implementation of climate action on agriculture, food systems and food security, understanding, cooperation and integration into plans" (UNFCCC, 2024).

Lastly, a thematic assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services of the interlinkages between biodiversity, water, food and health addresses the complex and interconnected character of the crises and challenges of biodiversity loss, water (availability and quality), food insecurity, health risks and climate change (IPBES, 2024). The response options presented in the report support the achievement of all SDGs, all targets of the Kunming-Montreal Global Biodiversity Framework and the long-term climate change mitigation and adaptation goals of the Paris Agreement.

Although the word "nexus" was dropped from the outlines of the Assessment Reports of IPCC Working Groups I, II and III during the final approval session and replaced with the word "intersection"[21], the need for an integrated approach in the analysis of human-caused impacts on natural resources and ecosystems remains prominent (IPCC, 2021, 2022a, 2022b)[22]. Indeed, in both plural and singular forms, the word "intersection" is used 3 times, the word "interaction" 14 times, the word "interconnection" twice, the word "interlinkages" twice, the word "integration" 17 times, the word "synergies" 21 times and the word "trade-offs" 9 times.

[19] The WEFE nexus approach uses context-specific solutions based on different levels of intervention to achieve long-term economic, environmental and social goals. More information can be found at: https://international-partnerships.ec.europa.eu/policies/climate-environment-and-energy/water-energy-food-ecosystem-nexus_en.

[20] The programme can be found at: https://www.water-energy-food.org/

[21] See IPCC (2022b), Chapter 14: Integration and interactions across sectors and systems. Intersections between water, energy, food, ecosystems and climate change; food systems; bioeconomy.

[22] Both in terms of qualitive and quantitative impacts (availability/productivity).

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3. Soil

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3.1. SOIL CARBON MANAGEMENT FOR MITIGATION AND ADAPTATION IN CROPLANDS

3.1.1 NO OR REDUCED TILLAGE

Since the IPCC (2019a) Special Report on Climate Change and Land, there has been further evidence that no or reduced tillage practices are effective strategies for long-term soil carbon management, contributing to climate change mitigation and adaptation in croplands. However, it is becoming apparent that the effectiveness of no or reduced tillage in increasing soil carbon is enhanced by complementary practices such as residue retention and manure application (see, for example, Lin *et al.*, 2023). Even so, evidence shows that continuous no-tillage systems are not always effective in supporting crop productivity goals, as they may increase soil compaction and weed pressure (Scarlato *et al.*, 2024), as well as the stratification of soil organic matter and nutrients (Mihelič *et al.*, 2024).

The compaction challenge can be addressed with occasional or strategic tillage (for example, every 5—10 years) aimed at improving crop production conditions compared with continuous no-tillage systems (Peixoto *et al.*, 2020; Wang *et al.*, 2023). Despite the potential of occasional tillage events to increase soil erosion immediately afterwards, they mitigate the negative impacts of no tillage by providing short-term benefits, such as reducing soil compaction and weeds, and lead to the stratification of organic matter and nutrients (Blanco-Canqui and Wortmann, 2020). An alternative to occasional tillage is reduced tillage (disc tillage), which is more effective than no tillage for managing soil compaction, particularly at deeper soil depths (Blanco-Canqui *et al.*, 2022). Another approach is to combine no-tillage farming with cover cropping to improve nutrient cycling, reducing the need for herbicides and the quantity of residual chemicals (Daryanto, Wang and Jacinthe, 2020). However, crop residue retention may result in a considerable amount of crop residues being left in the field, forcing farmers to practice widespread residue burning to ensure timely planting/sowing of succeeding crops (Somasundaram *et al.*, 2020).

Non-inversion tillage (subsoiling) has also been shown to effectively alleviate compaction in no-tillage systems for 17 months, with a possibility of extending the benefits by integrating additional soil management practices, such as cover cropping, diversified crop rotations and controlled traffic farming (Peralta *et al.*, 2021). A study conducted in Sweden reported that controlled traffic farming increased topsoil compaction in wheel tracks, but not within the cropping area (Etana *et al.*, 2020). There are, however, several economic, technological and knowledge barriers to the adoption of controlled traffic farming (Tamirat *et al.*, 2022). In contrast to the common notion that no-tillage systems reduce soil erosion, a recent study observed that due to a combination of factors, such as disruptive soil mixing, soil cohesion and tillage speed and depth, non-inversion chisel ploughing increased soil erosion compared with moldboard ploughing (Öttl *et al.*, 2022).

A meta-analysis of the effect of no-tillage systems on CH_4 fluxes showed lower CH_4 emissions under no-tillage systems (Maucieri *et al.*, 2021). The authors speculate that these reductions may be due to a combination of factors, including increased soil aeration due to improved soil structure, lower soil temperatures decreasing methanogenesis, and soil moisture variation favouring methanotrophy (Maucieri *et al.*, 2021). A study conducted in Northeast China showed that strip tillage systems maintain high yields and mitigate overall GHG emissions. but increase N_2O emissions (Wang *et al.*, 2024). The authors attribute the increase in N_2O emissions to the interaction of soil factors (that is, residual nitrate, water-filled pore space and temperature) in the case of strip tillage compared with conventional tillage systems without straw (Wang *et al.*, 2024).

The adoption of no-tillage systems at scale is a challenge that can be alleviated by gaining an in-depth understanding of farmers' sources of information and decision-making processes, and by taking advantage of farmer-to-farmer informal networks (Ogieriakhi and Woodward, 2022; Skaalsveen, Ingram and Urquhart, 2020; Bavorová *et al.*, 2020).

3.1.2 MULCHING, COVER CROPS AND GREEN MANURES

What do we know from Intergovernmental Panel on Climate Change reports?

- The AFOLU sector can provide 20–30 percent (interquartile range) of the global mitigation needed for a 1.5 °C or 2 °C pathway towards 2050. The sector offers significant near-term mitigation potential at relatively low cost, of 8—14 $GtCO_2e$/yr between 2020 and 2050 (Hurlbert *et al.*, 2019).
- Agriculture has the second-largest share of the mitigation potential, with 4.1 (1.7–6.7) $GtCO_2e$/yr (up to USD 100/tCO_2e) from cropland and grassland soil carbon management and organic amendments (Nabuurs *et al.*, 2022).
- In addition to contributing to mitigate between 0.03 $GtCO_2e$/yr and 0.71 $GtCO_2e$/yr between 2020 and 2050 (Jia *et al.*, 2019), improved cropland nutrient management could enhance food and nutrition security and wider environmental sustainability goals (Nabuurs *et al.*, 2022).
- Cropland nutrient management (such as cover crops, green manures and mulching) are particularly applicable and efficient in all regions and have the greatest mitigation potential in developing countries (Nabuurs *et al.*, 2022), where there is vast land for crops, a large number of farmers and high starvation levels.

Cover crops, green manures or mulching in managing soil carbon for mitigation, adaptation and climate change resilience

Globally, agriculture and food production systems account for about one-third of anthropogenic GHG emissions, of which 40 percent originates from agricultural production and 32 percent from land use and land-use change (Crippa *et al.*, 2021). In addition to being an emissions source, agricultural systems can also mitigate climate change if they act as a net carbon sink (IPCC, 2022). Reducing emissions and enhancing carbon storage and sequestration in agriculture will, therefore, require an enormous transformation of agricultural systems. This involves the implementation of low-carbon farming systems (also known as climate-smart agricultural systems), which encompass conservation agricultural practices such as cover cropping, mulching and green manuring.

Agricultural practices of cover cropping, mulching and crop residue manuring without excluding conservation tillage can restore depleted soil organic matter. These methods, when used effectively, have the prospect of sequestering 0.9 GtCyr-1 into the soil, which could offset 25 percent to 34 percent of the annual increase in CO_2 in the atmosphere (Nazir *et al.*, 2024). Covering about one-third of the soil surface with crop stubble and organic material can conserve soil moisture, reduce erosion and evaporation, and increase biodiversity and microbial activities. This, in turn, promotes soil carbon accretion and decreases emissions.

The potential of cover crops and organic manures in climate change resilience is indispensable to the world's carbon systems. These agricultural strategies can enhance microbial activities that increase soil organic carbon (SOC) stocks and improve soil health, food security and biodiversity. In Brazil, cover crops (such as vetch, soybeans, beans, ruzigrass, radish, black oat and sun hemp) were observed to have increased SOC stocks (see, for example, Besen *et al.*, 2024; Locatelli *et* *al.*, 2025). For the savannah region (Cerrado), Locatelli *et al.* (2025) modelled SOC dynamics in a crop-diversified system with crop rotation and cover crops and observed that the system accumulated high amounts of SOC (0.71 tC/ha/yr), corresponding to SOC stocks of about 130 tC/ha for 50 years of study. In southern Brazil, the integration of cover crops with no tillage produced a remarkable amount of SOC stock, at about 80.22 tC/ha (Besen *et al.*, 2024). A six-year experiment in Argentina revealed that cover crops increased by about 0.36 tC/ha/yr (Restovich *et al.*, 2019).

Similarly, in China, a study investigated the effect of cover crops on the physical fractions and chemical compositions of SOC, and found that SOC increased by 38 percent under legumes and 16 percent in non-legume cover crops — both of which were significant increases compared with the control plots without cover crops (Jian *et al.* 2020). In Malawi, heat-stress impacts on maize grain and biomass yields were suppressed to achieve optimal productivity by applying conservation agricultural practices, including green manures and crop diversification (Steward *et al.*, 2019). In South Africa, a study by Smith *et al.* (2021) introduced cover crops such as hay for grazing and legume-based cover-crop mixtures with wheat. The presence of cover crops was found to increase productivity during the study periods. A four-year study in Germany reported 5 percentage-point and 10 percentage-point increases, respectively, in the annual rate of change for soil organic nitrogen and SOC under cover crops compared with a business-as-usual scenario (Attia *et al.*, 2024). Some global meta-analyses have affirmed the significance of cover crops and organic residues as sustainable use and management for soil health indicators and SOC accrual (Brichi *et al.*, 2023; Vendig *et al.*, 2023; Jian *et al.*, 2020).

Furthermore, a recent study on Europe revealed that sowing cover crops before maize yielded a climate change mitigation of 49.8 $MtCO_2e$/yr, or about 13 percent of the European Union's agricultural emissions (Schon, Gentsch and Breunig, 2024). This underscores the vital role of cover crops in reducing the agricultural impact of climate change. Cover crops can make a positive contribution to soil carbon accumulation in indirect ways by providing fodder, plant nutrients and proteins, and biofuels (Muneer *et al.*, 2021; Launay *et al.*, 2022). A recent six-year field study in China, where diversified rotations were integrated with cover crops, showed that yields increased by up to 38 percent, N_2O emissions were reduced by 39 percent and the GHG balance was enhanced by 88 percent (Yang *et al.*, 2024). The bioeconomic and environmental benefits of cover crops help to reduce GHG emissions by creating substitutes for synthetic fertilizers and fossil fuels, especially in the current geopolitical environment (World Bank, 2022).

In the drylands of the Middle East and North Africa, the contribution of conservation/resilient agriculture, including cover crops and the implementation of other integrated crop management practices, to environmental sustainability and food security were deemed vital. According to Devkota *et al.* (2022), the adoption of cover crops and other conservation agriculture practices has increased in the region for many reasons, including climate change, growing awareness of the degradation of land and water resources among farmers and decision-makers, as well as changes in dietary preferences and growing trends in the demand for, and prices of, legume crops. Similarly, in the semi-arid prairies of Canada, the introduction of diverse crop rotations, including legume cover crops, was observed to have a higher SOC stock than under traditional sole-cropping systems (He *et al.*, 2021).

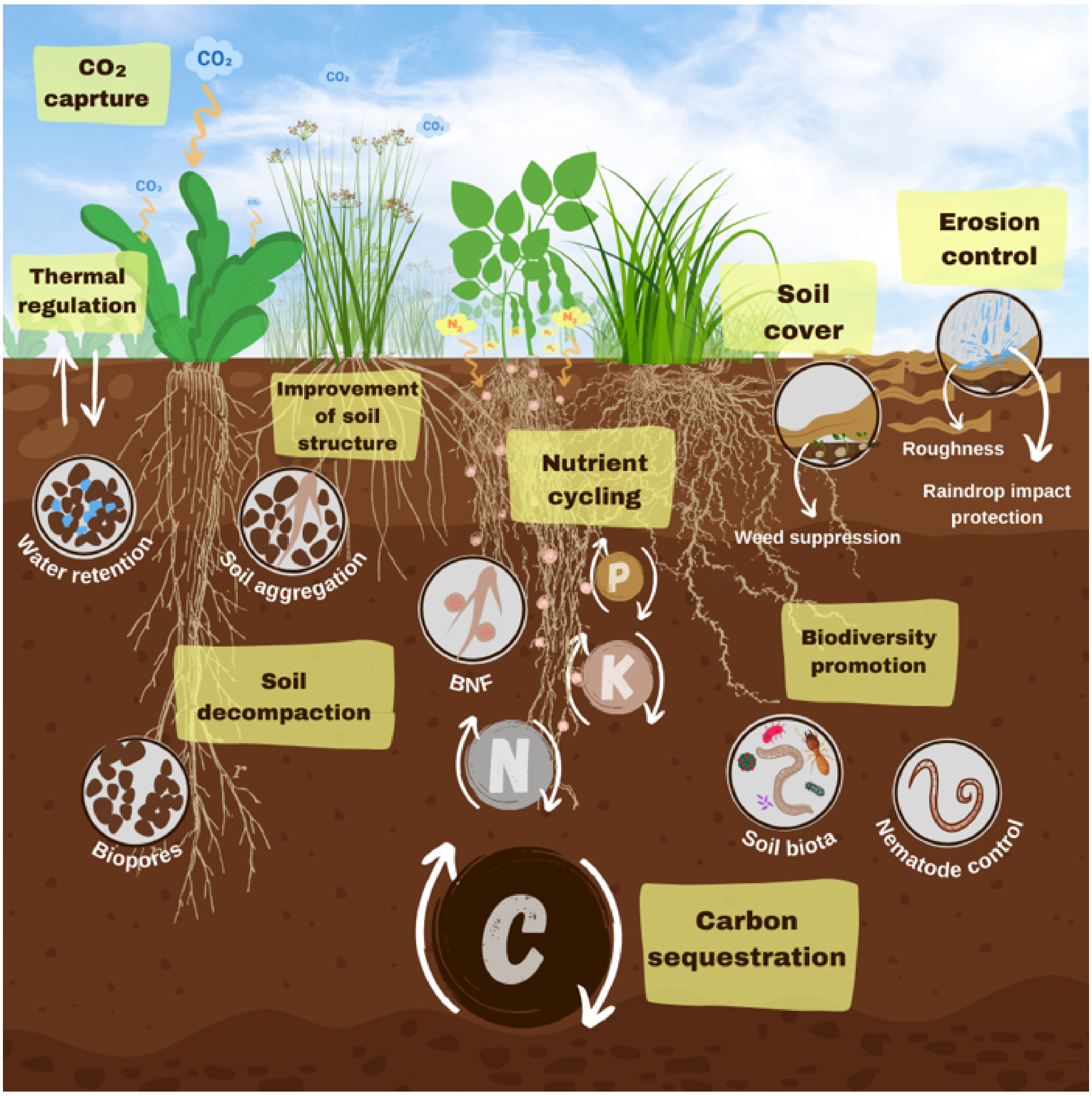
These recent studies and numerous others not presented here, summarize the multifunctionality of cover crops, mulching and green manures in mitigating climate change by increasing carbon storage and decreasing emissions, improving soil health and nutrient cycling, increasing agricultural productivity and food security, and controlling pests, diseases, weeds, erosion, evaporation and evapotranspiration. They also enhance the effective use of farm inputs and water-use efficiency, provide fodder and biofuel, and promote biodiversity and soil microbial activities. What is now important is to ensure the optimal and sustainable achievement of these benefits. It is also essential to understand the effects of cover crops during different seasons (growing and non-growing seasons) in different climatic regions. To achieve this, three things are necessary:

The establishment and consolidation of roadmaps for the long-term underpinning of SOC using cover crops, mulching and green manures

Soil carbon is a sensitive component that is susceptible to change, and its depletion tends to be faster than its accumulation. Major drivers of soil carbon release or depletion are rapid soil organic matter decomposition, soil erosion, CO_2 emissions, nutrient leaching and microbial decomposition, which are exacerbated by climate change (García-Palacios *et al.*, 2021). Therefore, for the safety of SOC, crucial measures need to be adopted to address these drivers. Mixing cover-crop species has been suggested to achieve multiple benefits of various grass, leguminous and non-leguminous broadleaf cover crops (Koudahe, Allen and Djaman, 2022; Cherubin *et al.*, 2024) (**Figure 3.1**). Sustainable intercropping supports carbon retention in the soil for longer, while legumes add nitrogen through biological fixation, improving the carbon—nitrogen ratio of crop residue.

The burning of crop residues, commonly practised by farmers in some developing countries, not only causes atmospheric pollution, but also leads to GHG emissions and the depletion of soil carbon (Russell-Smith *et al.*, 2021; Bhuvaneshwari, Hettiarachchi and Meegoda, 2019). To guarantee an increase in or the long-term storage of carbon in the soil, mulching materials should be carefully selected to ensure that residues with high carbon—nitrogen ratios are applied to increase soil organic matter and SOC, in contrast to low-carbon/nitrogen mulch, which may lead to the release of CO_2 and N_2O (Wei *et al.*, 2022). The benefits of mulching are recognized in many crops, but are particularly well documented for sugarcane in Brazil, where green harvesting (without burning) has become mainstream in the last two decades (Cherubin *et al.*, 2021).

FIGURE 3.1. Multifunctionality of cover crops in agroecosystems



Source: Illustration by Bruna E. Schiebelbein. Adapted from Cherubin, M.R., Vanolli, B.D.S., Souza, L.F.N., Canisares, L.P., Pinheiro Junior, C.R., Schiebelbein, B.E., *et al.* 2024. Practical guide to cover crops: species, management and impact on soil health. São Paulo, Brazil, University of São Paulo, Luiz de Queiroz College of Agriculture. https://doi.org/10.11606/9786587391618

Dynamism and sensitivity in crop species, complementarity, environment and management of cover crops for climate change mitigation

Cover-crop management options and soil-environmental suitability for optimal climate change mitigation are critical issues to be considered in farming systems. For instance, the quantity of carbon and/or nitrogen discharged into the soil by cover crops depends on many drivers, such as the length of the growing season, cover-crop species (legume or non-legume), quantity and quality of available biomass (such as the carbon/nitrogen ratio), the soil environment (for example, type, texture, moisture and temperature) and management (for example, tillage) (Abdalla *et al.*, 2019; Tariq *et al.*, 2024). In a study by Abdalla *et al.* (2019), it was found that legume cover crops saw a substantial increase in N_2O emissions, while non-legume cover crops, or a mixture of legume and non-legume cover crops, saw no significant increase in emissions. The high carbon–nitrogen ratio of non-legume cover-crop residues could be the reason for the insignificant increases in emissions.

In terms of growing seasons, a remarkable increase in off-season N_2O emissions was observed when a cover-crop mixture was applied, which was exacerbated in autumn, when sowing took place after the cover crop (Gao *et al.*, 2023a). In another recent study in southern Brazil, different tillage systems and winter cover crops (common vetch, fodder radish and black oat) were adopted to ascertain their effects on soil carbon stock and maize yield. It was found that although vetch showed an increase in maize yield in conventional and reduced tillage, it had the lowest carbon stock in tillage, but higher SOC in no-till situations (Besen *et al.*, 2024). This could be attributed to its lower dry matter production and carbon input, which diminished its soil carbon stocks relative to either fodder radish or black oat. Furthermore, below-ground microbes and root microbiota, including arbuscular mycorrhizal fungi, respond differently to different environments, different cover-crop species and different management practices (Benitez-Alfonso *et al.*, 2023). Therefore, careful selection of the most suitable cover crop–intercropping combinations, depending on the environment, is vital to promote carbon sequestration and mitigate climate change.

The dual nitrification and urease inhibitor model and other sustainable management approaches

Cover crops, mulching and green manures are viable agronomic practices for increasing carbon stocks, promoting yield stability, reducing dependence on agronomic inputs and diminishing carbon and nitrogen losses (Nilsson *et al.*, 2024). However, they can increase soil N_2O emissions as a result of the anaerobic microbial conversion of cover-crop decomposition products (Schon, Gentsch and Breunig, 2024). Inasmuch as some studies have observed the capability of cover crops to reduce N_2O emissions with an increase in carbon stocks (Nilsson *et al.*, 2024), cover-crop cultivation may also induce the elevation of N_2O emissions (Tariq *et al.*, 2024). For example, in the temperate zone, oilseed radish is a fast-growing cover crop that significantly contributes to carbon stocks, but it could be more liable or prone to N_2O emissions during freeze-thaw events than other frost-tolerant cover crops (Olofsson and Ernfors, 2022). The risk of elevated N_2O emissions is particularly high during freeze-thaw events in winter, as they can cause nitrogen and carbon in cover-crop biomass to be released into the soil in conditions favouring high denitrification levels (Olofsson and Ernfors, 2022). This could counterbalance the climate mitigation effect obtained by increased SOC stocks. Although cover cropping could be a remarkable nature-based solution to reducing the climate impact of agricultural systems, few studies have examined its effect on the emissions of other elements. In a global meta-analysis that considered the role of mulching on GHG emissions from agricultural systems, it was found that straw mulching reduced CH_4 emissions by 61.4 percent, increased N_2O emissions by 89.1 percent, reduced global warming potentials by 47.5 percent and improved water-use efficiency by 40.9 percent relative to continuous flooding irrigation (Gao *et al.*, 2023b).

Using cover crops and organic fertilizers (such as green manures and composts) helps to improve carbon content, soil health and crop productivity. However, due to their lower carbon/

nitrogen ratios in some cases, their application to soils can elevate the discharge of N_2O, offsetting the benefits of greater soil carbon and contributing to global warming (Kareem *et al.*, 2022). To counter this increase in N_2O emissions, one sustainable strategy could be to apply dual nitrification and urease inhibitor (dNUIs) after cover-crop discontinuation during nitrogen fertilizer addition (Tariq *et al.*, 2024). For example, in a recent study conducted in Canada, the application of dNUIs caused a 19 percent reduction in N_2O intensity within the diverse cover crop-cereal rotation. Machado *et al.* (2020) also observed a decline in annual N_2O emissions after the application of dNUIs in the continuous corn rotation, though N_2O emissions from the decomposition of cover could also be partly responsible if cover-crop residues were not incorporated into the soil. Moreover, while no-till practices could also contribute to N_2O emission reductions, the diverse mix of cover crops (grasses, legumes and non-legumes) is a way to partly ameliorate the effects of N_2O emissions. What is more, the introduction of a four-way or two-way cover-crop mixture after the main cash crop(s) can also be a good solution to intensified N_2O leaching. For instance, a study in Ontario reported a 67 percent decrease in nitrate leaching during the non-growing season by incorporating a four-way cover-crop mixture after the winter wheat harvest of a diverse corn–soybean winter wheat rotation (Lapierre *et al.*, 2022). Similarly, in Maryland, a two-way cover-crop mixture planted after corn resulted in an 80 percent reduction in annual nitrate (NO_3-) leaching (Gaimaro, Timlin and Tully, 2022).

In addition to the management strategies mentioned, more extensive field studies are recommended to ascertain and validate the effectiveness of the dNUI approach in ameliorating NOx (N_2O and NO_3-) emissions in cover crops and green manures in agricultural systems. This could potentially enhance soil carbon stocks and mitigate climate change without heightening the emission effects of any other GHGs that might negate the prime purpose of cover crops and organic amendments (such as mulching and green manures).

BOX 3.1. Soil carbon sequestration for land and soil sustainability

What is required to advance the concept of soil carbon sequestration for land and soil sustainability?

Land-based options that deliver carbon sequestration in soil or vegetation, such as afforestation, reforestation, agroforestry, soil carbon management on mineral soils or carbon storage in harvested wood products, do not continue to sequester carbon indefinitely. Peatlands, however, have been able to sequester carbon for centuries. Many land management options, such as improved management of cropland and grazing lands, improved and sustainable forest management, and increased SOC content, do not require land-use change and do not create demand for more land conversion.

Soil carbon footprints, climate-smart soils and carbon farmers in a climate change movement

Soil carbon sequestration – the removal of CO_2 from the atmosphere by photosynthesis – has a role to play in mitigating GHGs to reduce carbon footprints. Soil carbon footprints, therefore, could be useful in identifying and preserving climate-smart soils (Paustian *et al.*, 2016; Bhattacharyya, Narkhede and Haldankar, 2024). If farmers maintain climate-smart soils in accordance with appropriate management practices, they could see benefits in the form of soil carbon trading. Farmers' efforts to sustain climate-smart soils to help protect soil and mitigate climate change should be rewarded. Soil carbon management efforts could, therefore, connect farming communities with a global movement. Climate-smart soils could be identified, mapped and inventoried globally to inform land users and farmers.

Extension of research findings to help stakeholders

A 2010 discussion paper by the International Food Policy Research Institute opened with a question: are farmers' information needs being met (Glendenning, Babu and Asenso-Okyere, 2010)? Agricultural extension systems, such as that developed by Wani, Raju and Bhattacharyya (2021), are expected to extend such technologies through e-extension, which could then capitalise on concepts such as climate-smart soils, enabling appropriate management. This agricultural extension system has several parallel channels of information for farmers, so the focus is on proper information pathways to help stakeholders and bring farmers together as a part of a global movement to combat climate change (Glendenning, Babu and Asenso-Okyere, 2010).

3.1.3 NUTRIENT MANAGEMENT AND SOIL AMENDMENTS

What needs to be known about nutrient management, soil amendments and greenhouse gas emissions?

Mitigating soil N_2O emissions is essential if the world is to remain below the 2 °C warming threshold. However, accurate assessments of mitigation potential are limited by uncertainty and variability in direct emission factors. Recent research suggests that emission factors may be affected by an increase in background emissions (Zhang and Niu, 2020; Yin *et al.*, 2021).

At the global and regional scale, variations in emission factors tend to be driven primarily by climatic conditions, particularly in temperate areas (Jiang *et al.*, 2024), and edaphic factors rather than the well-recognized management practices (Yao *et al.*, 2024; Cui *et al.*, 2021). At the local scale, management-related variables tend to be more important. Yield-scaled N_2O emissions for individual crops are generally higher in tropical or subtropical zones than in the temperate zone and show a trend towards lower intensities from low to high latitudes (Zheng *et al.*, 2023; Cui *et al.*, 2021).

Technology-driven solutions (such as enhanced-efficiency fertilizers, chemical inhibitors, drip irrigation and biochar) and the optimization of fertilizer rate have considerable mitigation potential (Ma *et al.*, 2023; Grados *et al.*, 2022). Agroecological mitigation practices (such as organic amendments), while potentially contributing to soil quality and carbon storage, may exacerbate N_2O emissions and only lead to reductions under certain soil and farming conditions. Despite the variable mitigation potential, several mitigation practices may maintain or increase crop production, presenting relevant alternatives for policymaking to reduce GHG emissions and safeguard food security (Grados *et al.*, 2022). Also, synergies between more than one mitigation practice or technology implemented at a field scale offer an opportunity to increase cost efficiency for farmers, favouring adoption, but field-scale evaluations of stacked mitigation options are still rare.

Special attention should be paid to the use of increasing nitrogen inputs in agrifood systems in tropical regions (Hudell *et al.*, 2020) and emerging economies as agricultural production increases, as strict nitrogen pollution controls have been introduced in many developed regions (Harris *et al.*, 2021).

Role of background nitrous oxide emissions in soil nitrous oxide emission factors

To estimate soil N_2O emission factors, N_2O emissions are measured following nitrogen application to soils (inorganic or organic sources) and compared with emissions from untreated soils (control treatments) to account for background emissions (IPPC, 2006). Background N_2O emissions (BNEs) are defined as emissions from soil that have not received nitrogen fertilizer or excretion during the previous year, with N_2O emissions being the result of natural microbial nitrification and denitrification processes driven by nitrogen fixation, atmospheric nitrogen deposition and the mineralization of soil organic matter or crop residues (Zhang and Niu, 2020). Accurate estimation of BNEs is key to determining the N_2O emission factors used in inventory compilation and to understanding the N_2O sources in the natural ecosystem (Bowman *et al.*, 2002). Previous research assumed that BNEs did not change significantly with time, with efforts focusing on understanding the effect of key agricultural practices on N_2O emissions and developing country-specific emission factors for national GHG inventory reports. Nevertheless, recent research suggests that BNEs show an increasing trend over time, particularly in cropping systems in high-emission areas (Zhang and Niu 2020, Yin *et al.*, 2021) and grasslands (Yin *et al.*, 2021). There is a need to determine whether these changes in BNE are real and, if so, how they have affected estimates of emission factors. This will increase the accuracy of prior calculations and improve the transparency of national GHG inventories under the Paris Agreement, as well as NDCs, as inventory data provide the basis for tracking progress towards emission-reduction goals.

Nitrous oxide emissions and soil organic carbon interactions

There is a strong connection between soil nitrogen and carbon cycles, although the interaction between carbon and nitrogen cycles is still poorly represented in models. Nitrogen is bound to carbon in soil organic matter and through microbial activity (Poffenbarger *et al.*, 2017; Feng *et al.*, 2021). Studies have shown that SOC storage increases with nitrogen rates applied in nitrogen-deficient agroecosystems, while when nitrogen is in excess, added nitrogen increases residual inorganic nitrogen, enhancing SOC mineralization, thereby reducing the rate of SOC storage (Poffenbarger *et al.*, 2017). In addition, intrinsic soil organic matter characteristics may provide mineral protection to microbial action. Climate mitigation induced by increased SOC storage is then generally overestimated if associated N_2O emissions are not considered. A better understanding of such interactions is necessary to evaluate the benefits of different management practices aimed at increasing SOC storage and to predict the full GHG balance of each practice. Some sequestration strategies (such as biochar or non-pyrogenic organic amendment application) may create win-win situations by decreasing N_2O emissions, although the experimental evidence is still scarce (Guenet *et al.*, 2020).

Nutrient application strategies

Agriculture is responsible for about 84 percent of global anthropogenic N_2O. Nitrogenous fertilizer plays a crucial role in N_2O emissions from agriculture, accounting for around 60 percent of global anthropogenic N_2O emissions.

Several mitigation technologies have been developed and are already available. The global mitigation potential from cropland associated with nitrogenous fertilizer reduction has been estimated at 0.30 (0.23–1.44) MtN_2O-N/yr. This is equivalent to 30 percent (17–53 percent) of global direct emissions of N_2O from cropland and to the sum of direct soil emissions from China and the United States combined, although the distribution of this mitigation potential is not homogenous and a mix of national and regional policies could be improved to better target local environmental conditions critical to assessing the mitigation potential more accurately (Cui *et al.*, 2021).

The fast-growing number of studies assessing N_2O mitigation practices and synthesis-based research allows the simultaneous comparison of the N_2O mitigation potential of prominent mitigation practices, enabling a robust ranking of their mitigation efficiency (Grados *et al.*, 2022), although uncertainty remains with regard to synergies and trade-offs associated with the implementation of specific management techniques and technologies (Chen *et al.*, 2020; Eagle *et al.*, 2017).

Slow-release fertilizers

Bio-based coatings of fertilizer products have been evaluated for their ability to slow the release of nitrogen from fertilizer granules, helping to synchronize nitrogen supply with plant demand, potentially reducing N_2O emissions (Priya, Sudipta and Pradip, 2024). Further research is required to understand the interactions of soil and climate conditions affecting the performance of these alternative sources, as well as their implications for the economic viability of different agrifood systems.

Nanofertilizers and bionanofertilizers

These materials have been identified as promising options that can be blended with or coated onto nitrogenous fertilizers to give them slow-release characteristics. These materials have a high surface area, high reactivity and/or high porosity and, therefore, a greater capacity to adsorb nutrients than bulk materials offering opportunities to reduce N_2O emissions (Hube *et al.*, 2022; Wu *et al.*, 2018) or increase soil carbon sequestration (Mason *et al.*, 2023). There is a need to evaluate the effectiveness of these materials at field scale for different crops and pastures, understanding the interactions with representative soil and climate conditions affecting the performance of these alternative sources. In addition, the incorporation of potential residues into the food chain needs to be better evaluated and understood.

Organic amendments and microbial solutions

Organic amendments play multiple roles in the microbially mediated reactions that lead to N_2O production, resulting in positive or negative effects. The nature of the organic amendments greatly affects emissions from soils with risk categories, providing an opportunity to account for the N_2O emissions from specific organic amendment sources or groups of organic amendments with similar characteristics (Charles *et al.*, 2017). Variations in N_2O emission factors in organic-amended soils are influenced mainly by the mineral nitrogen content and the carbon/nitrogen ratio of organic amendments, rainfall (expressed as total annual precipitation), soil texture and drainage. Further analysis is required to determine more specific emission factors that reflect the variation in organic amendment sources, as well as the interactions with soil and climate (see, for example, Akiyama *et al.*, 2023).

Microbes are increasingly becoming part of sustainable agricultural systems, with plant growth-promoting rhizobacteria (Rhizobium and Pseudomonas) and fungi (*Aspergillus*, *Trichoderma* and vesicular-arbuscular mycorrhizae) are being used as biofertilizers, either single strained or in consortium approach, with the latter found to be more beneficial to plant and soil health (Sharma *et al.*, 2020). Nevertheless, the implications of these benefits for carbon sequestration (Mason *et al.*, 2023) and GHG mitigation (Wu *et al.*, 2018) are less known. Initial work suggests that fungi process plant carbon faster than bacteria and lock it into their biomass, also promoting the formation and stabilization of soil aggregates, considered one of the mechanisms for enhancing the stability of SOC (Ustun, Talip and Caner, 2023; Wilson *et al.*, 2009), thus potentially contributing to SOC sequestration. Further studies are required to adequately understand the contribution of these alternatives as mitigation options in a range of agricultural ecosystems, as well as to highlight the benefits of local biodiversity as a tool for reducing GHG emissions and increasing carbon sequestration.

Biochar bio-based fertilizers

The use of biochar-based fertilizers and the co-application of biochar with other mineral fertilizers have shown promising results for mitigating N_2O emissions and reducing nitrogen losses in agroecosystems (Castejon-del Pino *et al.*, 2023), although long-term evaluations under different cropping, soil and climate conditions are still needed to better understand more adequate pyrolysis conditions (Wang *et al.*, 2023), the influence of rate, depth and frequency of application (Shrestha *et al.*, 2022), and the legacy effect of biochar-based fertilizer application (Horák *et al.*, 2021). In addition, the characteristics and availability of biomass used for biochar production, as well as the energy cost equivalent of the generation, transport and application processes, remain significant challenges for the practical and economical potential of biochar as a method for decreasing N_2O emissions and nitrate leaching, while sequestering carbon (Guenet *et al.*, 2022). For further details, please see Section 3.1.4.

3.1.4 BIOCHAR

Biochar has been drawing interest on the international research agenda since 2000 (Joseph *et al.*, 2021). It is produced by the thermal transformation of organic matter in an oxygen-limited environment. Its properties vary depending on feedstock origins (for example, woody residues, crop straw, animal manures, sewage sludge and food wastes), temperature treatments (such as heating time and temperature range, from 350 °C to over 750 °C) and treatments applied before and after pyrolysis. A meta-analysis by Ippolito *et al.* (2020) reveals that feedstock selection has the largest influence on biochar properties, while pyrolysis temperature affects its longevity.

What have we learned from scientific reports about biochar soil amendments?

Mitigation potential

Biochar is recognized as a carbon dioxide removal (CDR) approach. The removal and storage of CO_2 through vegetation and soil management can be reversed through land management and natural disturbances, whereas carbon in biochar is less prone to reversal.

Biochar's mitigation potential is estimated at 0.03–6.6 $GtCO_2e$/yr by 2050 (IPCC, 2019a), of which 1.1 (0.3—1.8) $GtCO_2e$/yr is available up to USD 100/tCO_2).

Multiple impacts

A meta-analysis (Joseph *et al.*, 2021) suggests that biochar amendment in soils:

- Increases soil properties such as pH, porosity and water-holding capacity, but has no consistent effect on soil water infiltration (Acharya *et al.*, 2024). However, biochar may induce water repellence depending on feedstock composition, soil types and pyrolysis temperature (Acharya *et al.*, 2024).
- Increases crop yields by 10 percent to 42 percent, on average, with the highest impacts in sandy soils in drylands due to the positive impact of biochar on water-holding capacity.

Future actions needed to address knowledge gaps

- Integrate biochar into IAMs to assess the comparative impact of biochar with other CDR approaches:
  - to finetune mitigation potential at scales larger than the farm plot;
  - to jointly assess the impact of biochar on change in SOC stock versus N_2O and CH_4 emissions.
- Set up long-term field studies:
  - to unravel processes responsible for high water retention in different biochar-amended soil types (Acharya *et al.*, 2024);
  - to explore biochar management adapted to: i) feedstock diversity and availability, ii) local climate and iii) soil types;
  - to evaluate the cost-benefit of biochar amendments.
- Continue research into processes:
  - pyrolysis to design green technology for less reliance on fossil fuels;
  - biochar—plant—microorganism interactions;
  - interactions between biochar and pollutants;
  - biochar ageing in soils.
- Quantify the role of biochar in the circular economy.
- Promote an enabling environment for the dissemination of locally adapted biochar manufacturing.

3.2. SOIL CARBON MANAGEMENT FOR MITIGATION AND ADAPTATION IN GRAZING LANDS

3.2.1 WHAT HAVE WE LEARNED FROM THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE REPORTS?

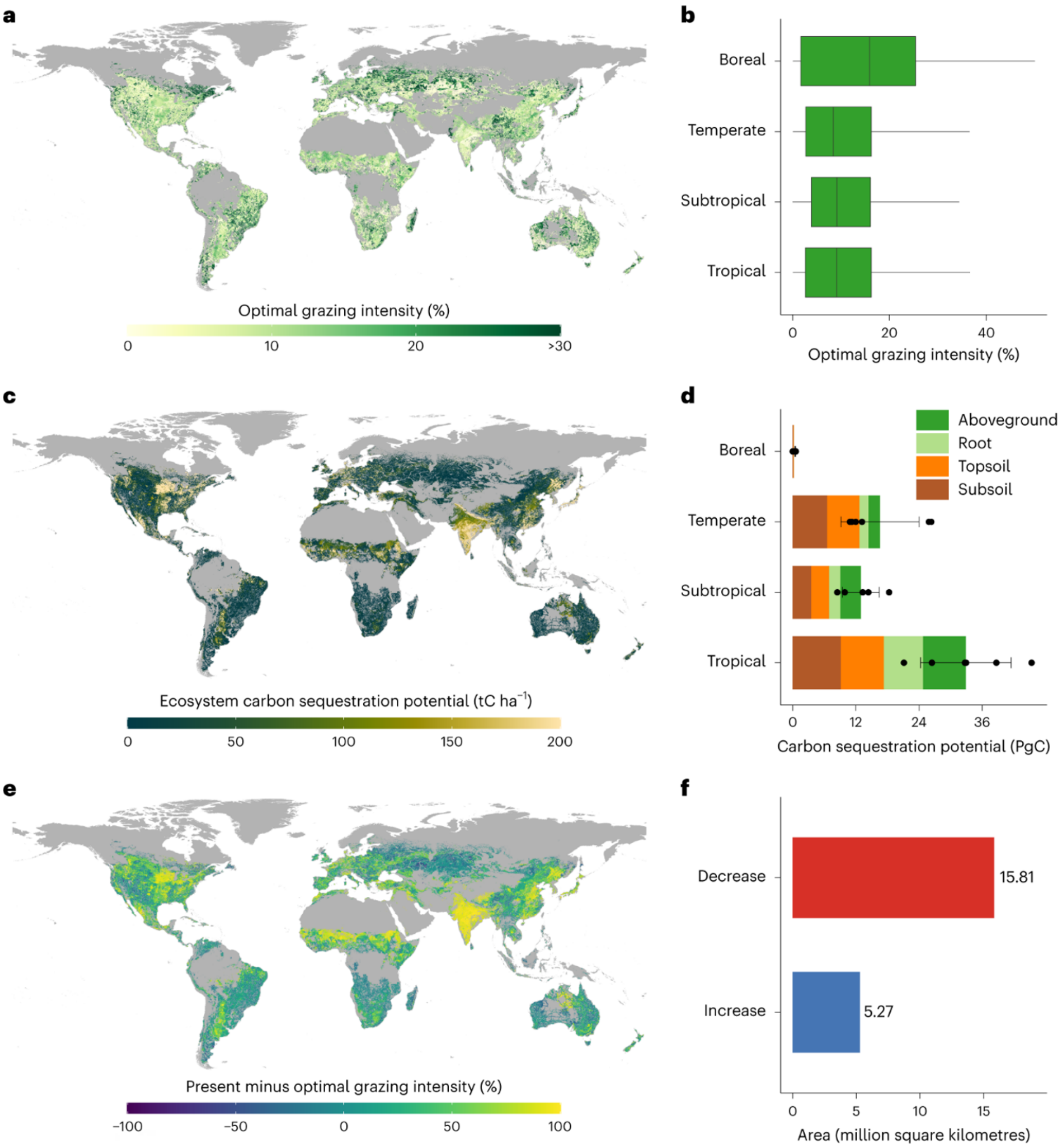
- Grazing land management is identified as one of the practices that can be optimized and scaled up to advance adaptation in food systems. It is also an option with great potential for mitigation in livestock systems.
- The impacts of climate change on global rangelands and livestock have received little attention compared with impacts on crop production. Projected impacts on grazing systems include changes in herbage growth and quality, and the composition of pastures. Droughts and high temperatures in grasslands can also be a predisposing factor for fire occurrence.
- In terms of impacts, there are large uncertainties related to grassland NPP and the length of growing period. There is also a lot of variability in the direction of change, both by region and grassland composition (for example, herbaceous cover, shrub cover or bare ground cover).
- Increasing variability in grazing systems has negatively affected animal fertility, mortality and herd recovery rates, reducing the resilience of livestock farmers.
- The IPCC (2019a) Special Report on Climate Change and Land identified the impact of interactions between grazing patterns and climate change on grassland composition as a knowledge gap. New knowledge has been developed on this topic since then.

Grazing systems emit GHGs, which can, under specific agroecological conditions, be partly or entirely offset by soil carbon sequestration (Godde *et al.*, 2020). However, there is no agreement on how the grazing management of extensive livestock systems can contribute to SOC sequestration. Such an agreement would have to consider that grasslands globally have different characteristics, so the same management practices may have different outcomes in different places. Grazing intensity values are context specific and vary greatly across ecozones, depending on land-use histories, as well as biotic and abiotic factors (Ren *et al.*, 2024). In addition, different species have different impacts on soil carbon sequestration (Ding *et al.*, 2024). Different management systems (such as continuous grazing and multi-paddock rotational grazing, or diverse forms of integrated crop–livestock systems, including those that combine bioenergy and livestock production) result in different GHG contributions and carbon sequestration potential (Wang *et al.*, 2021; Mosier *et al.*, 2021; Ayarza *et al.*, 2022; de Souza *et al.*, 2022;).

Mitigation estimates are also strongly influenced by the choice of intervention and the methods used in a given study. They are, therefore, associated with large uncertainties (Godde *et al.*, 2020). Jordon *et al.* (2024), following an extensive review, states that part of the disagreement among studies stems from the different methodologies used to measure carbon in soil and total emissions from grassland systems, as well as the units used in comparisons with other production systems. Very different results are obtained if emissions are compared per hectare of land versus per kilogram of product (Garnett, 2011). The latter is the most commonly used and disadvantages extensive animal systems. Also, different metrics used to calculate GWP — for example, GWP over 100 years (GWP100 in CO_2e) and GWP*, which describes additional warming as a function of the timeline of short-lived GHG emissions (measured in CO_2 warming equivalents, CO_2-we) — provide different results on the contribution of livestock systems to climate change (Hörtenhuber *et al.*, 2022; Berton *et al.*, 2024). It is also complicated to integrate factors such as point-based emissions from the manure produced in intensive systems. Furthermore, there are no standardized ways of accounting for the indirect effects of different production systems, such as displaced or replaced production (telecoupling effects) (see Section 10.3).

Ren *et al.* (2024) carried out a meta-analysis of 1 473 paired SOC observations from grazing studies conducted around the world over the past 60 years. The study estimated that on a 21 million km^2 area of grazing land, decreasing grazing intensity on 75 percent of the land and increasing it on 25 percent could result in a potential uptake of 63 ± 18 gigatonnes of carbon (GtC) in vegetation and soils (at a depth of 30–100 cm). Carbon accumulation potential from grazing optimization is higher in eastern North America and southern Asia (**Figure 3.2c**). The tropics (33 ± 8.6 GtC) stand out as having the highest mitigation potential, probably due to their larger opportunity areas (8.95 million km^2), followed by the temperate (16.6 ± 7.42 GtC; 6.89 million km^2) and subtropical (12.9 ± 3.5 GtC; 5.1 million km^2) zones (**Figure 3.2d**). In addition, around half of the mitigation potential (37 ± 13.5 GtC) would be present in soils (carbon accumulated in plants is estimated at 26 ± 8.1 GtC). Nonetheless, this value is less than a third of the soil carbon required to offset the GHG emissions from the global ruminant sector (135 GtC), indicating that relying solely on optimizing grazing is not sufficient to mitigate the warming caused by current ruminant systems.

FIGURE 3.2. Impacts of grazing on C and Climate Change mitigation potential



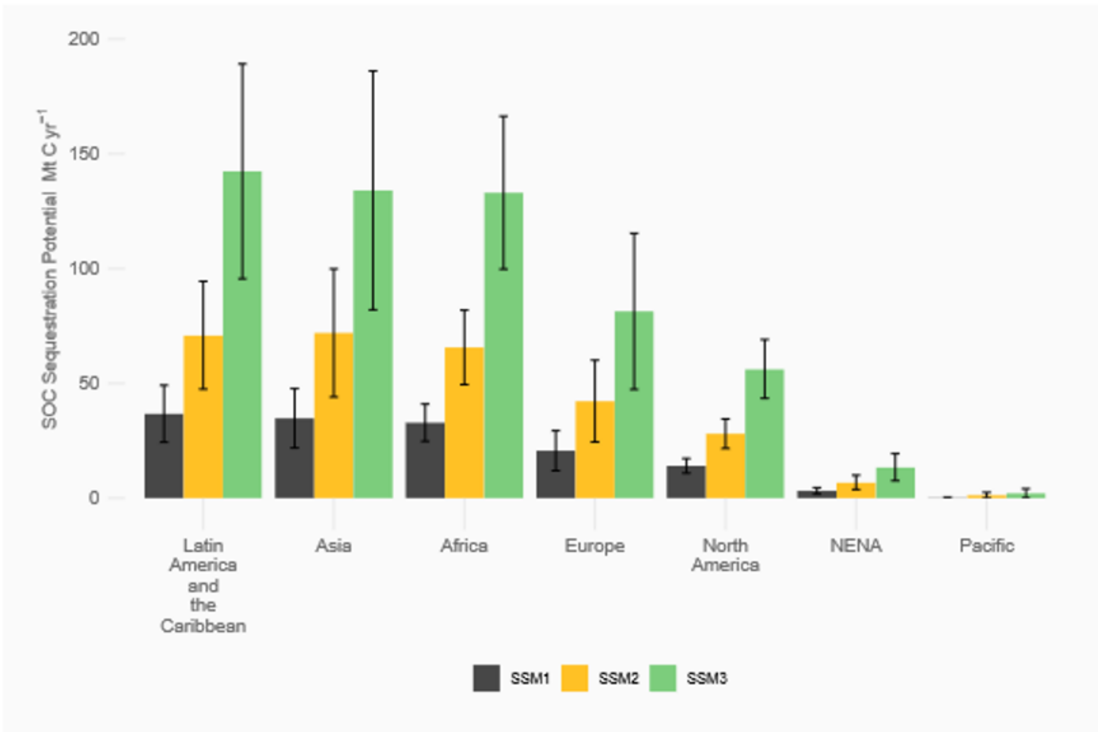
Note: **a,b** — Global optimal grazing intensity (GIopt), with the spatial pattern shown on a map (a) and aggregated by ecozone (b). **c** — Global distribution of ecosystem carbon sequestration potential (tC/ha) of grazing lands under the optimal scenario (a). **d** — The carbon sequestration potentials (in petagrams of carbon or in GtC) of above-ground, root, topsoil and subsoil were aggregated by different ecozones. **e** — Differences between present-day and optimal GI. **f** — Area of grazing land where the GI needs to be increased or decreased to reach the optimal level. Box plot shows the 25th and 75th percentiles (box borders), medians (central black lines) and data ranges (whiskers). Data in **d** are shown as mean values ± standard deviation for total carbon sequestration potentials across different plant and soil carbon datasets (n = 6).

Source: Ren, S., Terrer, C., Li, J. *et al.* Historical impacts of grazing on carbon stocks and climate mitigation opportunities. Nat. Clim. Chang. 14, 380–386 (2024). https://doi.org/10.1038/s41558-024-01957-9

Dondini *et al.* (2023) also estimated global SOC sequestration potential after 20 years of applying best management practices for all available grassland soils. The highest potential for SOC storage was found to be in the Russian Federation (average SOC stock of 191 tC/ha), However, these soils have probably reached their full sequestration potential, so the accumulation potential is limited. Sub-Saharan Africa and South Asia show the highest potential for carbon storage on a per-hectare basis (0.41 and 0.33 tC/ha/yr, respectively), followed by Oceania, North America and East Asia. Western Europe and Eastern Europe have the lowest annual increments (0.20 tC/ha and 0.18 tC/ha, respectively), which is negligible.

FAO (2022) also estimated the global carbon sequestration potential of sustainable soil management, considering different management options, ranging from 0.143 (+/- 0.05) GtC/yr for a low-carbon inputs sustainable soil management scenario to 0.566 (+/- 0.19) GtC/yr for a high-carbon-inputs sustainable soil management scenario. In its calculations, Latin America and the Caribbean, Asia and Africa were the regions with the highest sequestration potential (**Figure 3.3**).

FIGURE 3.3. Regional carbon sequestration potential versus a business-as-usual scenario



Note: Results for the Pacific region do not include Australia and New Zealand.

Source: FAO. 2022. Global Soil Organic Carbon Sequestration Potential Map – GSOCseq v.1.1: Technical report. Rome. https://doi.org/10.4060/cb9002en

In Australia, a recent review showed that despite the fact that no evidence exists that grazing management directly increases SOC, some practices (lower stocking intensity and rotational grazing) have the potential to benefit the drivers of SOC by increasing above- and below-ground plant production, maintaining a higher residual biomass and promoting productive perennial pasture species (McDonald *et al.*, 2023). Henry *et al.* (2024) found similar results using field trials and modelling studies for sequestration, adding that sowing more productive grasses or legumes in existing grass pastures generally increased SOC stocks; conversion from cropping to permanent pasture resulted in sequestration (influenced by management history); and water-ponding increased SOC stocks initially but no persistence was demonstrated. However, in remnant woodland areas in temperate regions, net sequestration of carbon can occur at farm scale through low-input management (Lawrence *et al.*, 2023).

There are knowledge gaps, however:

- Limited data exist to assess how environmental factors, such as climate, soil properties and vegetation affect soil responses to grazing management practices and how they interact with each other.
- There is limited knowledge on the influence of length of time in pasture on mineral-associated organic carbon accumulation in deeper soil layers in crop–livestock systems.
- More data are required to understand the contribution of livestock to climate change and how different metrics provide different results for different management systems.

3.3. SOIL CLIMATE INTERACTIONS

3.3.1 SOIL CARBON DIOXIDE RESPIRATION IN A WARMING ENVIRONMENT

What have we learned from the Intergovernmental Panel on Climate Change reports?

- The AFOLU sector accounts for about 23 percent of anthropogenic emissions of CO_2, CH_4 and N_2O (2007–2016). Increased emissions from vegetation and soils due to climate change in future are expected to counteract potential sinks due to CO_2 fertilization (Jia *et al.*, 2019).
- Ongoing warming will be responsible for new, hot climates in tropical regions, shifting climate zones, and ecosystems becoming increasingly exposed to temperature and rainfall extremes. Heatwaves are projected to increase in frequency, intensity and duration in most parts of the world (Jia *et al.*, 2019).
- Ecosystem responses to warming are not yet fully integrated into climate models (Arias *et al.*, 2022).

What needs to be known about carbon dioxide soil respiration in a warming environment?

Soil organic matter is one of the largest carbon sinks of terrestrial ecosystems, amounting to about 1 700 GtC (at 0—1m depth), while terrestrial, above-ground biomass amounts to 450 GtC

(Friedlingstein *et al.*, 2023). SOC stock depends on carbon input in the form of organic plant residues and exudates, rather than carbon output, respired as CO_2 by soil microorganisms. Global CO_2 emissions from LULUCF averaged 1.3±0.7 GtC/yr in 2013–2022, while total anthropogenic emissions were 11.1 GtC/yr in 2022. Carbon stored in soils is estimated to account for about 80 percent of the organic carbon resources actively involved in the global carbon cycle (Schlesinger, 1997). Consequently, SOC dynamics have received a lot of attention in earth system models, as a slight change in carbon inputs or/and carbon outputs may have a huge impact on CO_2 respiration and on climate in a feedback loop.

Soil organic matter decomposition is a biological process, controlled by a wide array of soil microorganisms interacting with each other, with other soil organisms and their environment. Several areas of research need to be tackled to improve the performance of earth system models in predicting SOC dynamics (storage versus respiration) in croplands facing climate change, particularly warming environments. There are three main priorities:

Temperature sensitivity of soil organic matter decomposition

Temperature sensitivity (Q_{10}) of ecosystem respiration (Re) is defined as a quotient of the change in respiration with a 10 °C increase in temperature. This is a critical parameter when determining global terrestrial carbon dynamics and their response to climate warming. Research studies have demonstrated that SOC stocks are inversely related to latitudinal gradients of NPP, with higher stocks being recorded at higher latitudes. This indicates that decomposition rates of organic inputs change faster as a function of temperature than NPP. Therefore, warming would lead to huge losses in the SOC responsible for positive feedback in CO_2 atmospheric concentration. Although, many research studies have explored means and methods of quantifying the Q_{10} of soi organic matter, uncertainties and contradictory results persist. Most earth system models use a Q_{10} value of 2.0, a few of them use a fixed value of 1.5, while others set Q_{10} at a constant value of 1.4 (Zhang *et al.*, 2024). Regardless, there is an urgent need to set an appropriate Q_{10} value for earth system models to improve their performance in predicting soil CO_2 respiration in the face of warming environments.

Soil microbial carbon use efficiency: a functional approach

In most earth system models, soil microorganisms (and enzymatic activities) are not well represented, despite being key drivers of soil organic matter decomposition and CO_2 respiration. The efficiency with which bacterial communities metabolize organic substrate into biomass, referred to as carbon use efficiency (CUE), is a key parameter determining the rate at which microbial communities decompose organic substrate and respire CO_2 (Manzoni *et al.*, 2012). Many investigations have been conducted to unravel the drivers of CUE. Sinsabaugh *et al.* (2013) recommend using a CUE value of 0.30, not that different from the meta-analysis (0.37) of Hu *et al.* (2022). Laboratory work shows that the impact of temperature on CUE is taxonomically structured, underlining the importance of an ecological approach (Smith *et al.*, 2021). Studies by Oliver, Houlton and Lipson (2021) and Tao *et al.* (2023) showed a positive correlation between CUE and SOC stock. Similarly, Ullah, Carrillo and Dijkstra (2021) demonstrated that interseasonal variations of soil microbial communities had a deeper impact on CUE than drought variations. Moreover, a meta-analysis by Trap *et al.* (2016) indicated that CUE decreased in the presence of bacterivores, highlighting the need to consider ecological trophic interactions in earth system models to increase their performance. At field scale, Sauvadet *et al.* (2018) revealed that the soil biotic legacy of different agricultural practices (such as reduced tillage compared with conventional agriculture) is one of the drivers of CUE in response to organic residue amendment. The impact of agricultural practices in determining the level of CUE in a warming environment has also been stressed. In addition, a 10-year investigation by Tian *et al.* (2024) indicated that warming enhanced the SOC increase in conservation agriculture (no tillage, chopped cropped residues), while SOC decreased in conventional agriculture (annual tillage, crop residues removed). A shift in microbial communities and an increase in fungi growth efficiency recorded under conservation agriculture explained this result.

More research is needed to understand the combined effects of sustainable land management and the ecological functioning of soil organisms and climate on the SOC cycle (sequestration versus respiration = CUE) to guide climate-smart land-use practices to optimize carbon budget and crop production in the face of climate change, and to make sure current good practices to balance crop production and soil carbon budget are still efficient in a warming world.

3.3.2 TEMPERATURE RESPONSES OF SOIL RESPIRATION

As highlighted in the IPCC (2019a) Special Report on Climate Change and Land, there is a consensus that higher temperatures will increase soil respiration. Recent studies confirm this response. For example, a study conducted in a subalpine meadow in Mount Wutai, China, reported a consistent increase in soil respiration rates of 2.00 micromoles per square metre per second (μmol/m2/s) with a 1.25 °C rise in soil temperature across different altitudes and seasons (Shuzheng *et al.*, 2023). A study on a semi-arid temperate steppe reported a 42.1 percent increase in soil respiration with a 1.48 °C increase in soil temperature during the non-growing season (Miao *et al.*, 2020).

There is further evidence of the importance of soil moisture in regulating the temperature response of soil respiration. For instance, a recent study reported a higher respiration rate at higher (60 percent water-holding capacity) rather than lower (30 percent water-holding capacity) soil moisture levels (Liu *et al.*, 2019). Studies have also shown that extended warming periods does not result in changes in respiration rates due to the thermal adaptation of microorganisms to high temperatures (Dacal *et al.*, 2019). Therefore, it is becoming unambiguous that heterogeneity in soil and climatic conditions is a major driver of uncertainty in the magnitude of temperature response to soil respiration.

In the case of subsoil, recent evidence confirms the high temperature sensitivity of subsoil carbon pools (Soong *et al.*, 2021). The loss of subsoil carbon is mainly due to the warming-induced decomposition of unprotected particulate organic matter (Soong *et al.*, 2021). In permafrost regions, a decrease in soil moisture and increase in warming was observed to result in a higher proportion of old SOC being vulnerable to decomposition and loss as CO_2 (Pegoraro *et al.*, 2021).

3.3.3 SEA-LEVEL RISE AND SOIL ACCUMULATION IN COASTAL WETLANDS

Soil accumulation in coastal wetlands has tracked the rate of sea-level rise over the last thousands of years of the Holocene (McKee, Cahoon and Feller, 2007;). While there are limits on the capacity of coastal wetlands to withstand sea-level rise, estimated at about 8 mm/yr for mangroves and tidal marshes (Saintilan *et al.*, 2023), moderate rates of sea-level rise lead to enhanced accumulation of sediments and soil carbon (Rogers *et al.*, 2019). This results from enhanced volumes of tidal water inundating coastal wetlands that deliver sediments and associated organic matter that are trapped within the wetland (Woodroffe *et al.*, 2016), as well as increases in the allocation of biomass to root systems, which can increase soil volume through the addition of organic carbon with root detritus (McKee, Cahoon and Feller, 2007). Consequently, in many coastal wetlands, there may be increased SOC accumulation until sea-level rise thresholds are exceeded. The elevation of coastal wetlands within the intertidal zone moderates the rates of soil accumulation (Woodroffe *et al.*, 2016; Saintilan *et al.*, 2023) and is, therefore, important in projecting soil accumulation (and SOC accumulation) and the persistence of coastal wetlands with sea-level rise.

3.3.4 SEA-LEVEL RISE AND SALINIZATION

The salinization of agricultural soils as sea levels rise is an emerging issue for coastal agriculture around the globe (Tully *et al.*, 2019; Corwin, 2021; Eswar, Karuppusamy and Chellamuthu, 2021). Sea-level rise can act synergistically with reduced rainfall, agricultural water use, rising groundwater and degraded infrastructure to reduce crop yields (Tully *et al.*, 2019). Restoration of coastal wetlands has been proposed as an alternative to agriculture once land is degraded (Borchert *et al.*, 2018; Tully *et al.*, 2019; Rowland *et al.*, 2023), but the restoration of coastal wetlands on the edge of agricultural land has also been shown to delay salinization (Kirwan *et al.*, 2024). This occurs as a result of the attenuation of tides by coastal wetlands, due to the friction offered by channels and vegetation, and the infiltration of tidal waters into wetland soils, as well as wetland soil accumulation, which maintains land elevation and reduces the tidal inundation of adjacent agricultural land (see, for example, Stark *et al.*, 2015).

3.4. PEATLANDS

3.4.1 PEATLAND'S ROLE IN ADDRESSING CLIMATE CHANGE

Peatlands serve as one of the world's most concentrated terrestrial carbon stores, containing about 644 GtC, or 21 percent of the total global SOC stock (IUCN, 2017; Leifeld and Menichetti, 2018). This carbon stored in peatlands is approximately twice the amount of carbon stored in all of the world's forest biomass (IPCC, 2022). Peatlands only account for around 3 percent of the terrestrial surface and predominately occur in boreal and temperate ecosystems, with a smaller proportion in tropical regions. When drained for agriculture or other land use, peatlands rapidly release stored carbon in the form of CO_2 and other GHGs, including N_2O, due to soil oxidation from microbial decomposition. Without further peatland exploitation or drainage, it is estimated that current drained, degraded and cultivated peatlands will cumulatively release 80.8 Gt of carbon and 2.3 Gt of nitrogen over the next few hundred years, corresponding to contemporary annual GHG emissions of 1.91 (0.31–3.38) $GtCO_2e$ (Leifeld and Menichetti, 2018).

Peatlands also play a crucial role in climate adaptation and biodiversity protection. For instance, in their natural, undrained state, peatlands can absorb and hold large volumes of water, acting like a natural sponge. This helps to reduce flood risks during heavy rains and ensures a steady release of water during dry periods, supporting nearby ecosystems and local communities. Wet peatlands lower ambient temperatures in surrounding areas, providing refuge from extreme heat, and are less likely to burn during wildfires, which release harmful smoke and haze that impairs air quality. Local communities' direct dependence on peatlands for food, fibre and fuel, or indirect reliance on them for a steady water supply, can be compromised, as peatland resilience is reduced when drained and degraded. Maintaining peatlands to withstand changes, including to their uses, cultural significance and current management, has implications for climate change, biodiversity conservation and development (Schulz *et al.*, 2019).

3.4.2 PRESSURES FACED BY PEATLANDS

Anthropogenic activities, including draining for agriculture or other purposes and mining, impact about 10 percent of global peatlands. These disturbances transform long-term peatland carbon sinks into sources through three carbon loss pathways: CO_2 from microbial peat oxidation; dissolved carbon leaching; and CO_2, carbon monoxide (CO) and CH_4 from peat fires and the combustion of mined peat (Leifeld and Menichetti, 2018). Drained peatlands also release significant amounts of N_2O (IPCC, 2013) . Climate change is accelerating the degradation of peatlands through warming temperatures, altered precipitation patterns and increased frequency of droughts and fires. Drought conditions heighten fire risk, particularly in drained and converted peatlands, leading to severe carbon losses. For example, the 2019–2020 fires in Indonesian peatlands emitted more CO_2 in a few months than some industrialized nations emit annually, severely impacting local air quality and global carbon budgets (Field *et al.*, 2020). These climate pressures exacerbate soil oxidation and increase emissions, making peatlands particularly vulnerable to elevated GHG release when exposed to a higher risk of wildfires and accelerated degradation (Wilkinson *et al.*, 2023).

With growing agricultural demand, peatland areas are increasingly being drained and converted for crops, including oil palm and soy, particularly in Southeast Asia and South America. According to recent estimates, peatland drainage and land-use change account for 4 percent of total anthropogenic CO_2 emissions, making their management critical to climate change mitigation efforts (Global Peatlands Initiative, 2022). A global assessment found that about 12 percent of current peatlands are degraded to the extent that peat is no longer forming or is unstable, and that the accumulated peat carbon stock is being lost (Global Peatlands Initiative, 2022). Around 11 percent of global peatlands (50 Mha) are facing degradation annually (Leifeld and Menichetti, 2018), of which 5 percent are in tropical regions, 3 percent in the temperate zone, 2 percent in the boreal region and less than 1 percent in the polar regions (Global Peatlands Initiative, 2022). Consequently, peatland protection and restoration are seen as important mitigation measures. In particular, restoration through rewetting can significantly reduce GHG emissions (Wilson *et al.*, 2016), restore vegetation communities and recover biodiversity, while still allowing for extensive management such as paludiculture (Leifeld and Menichetti, 2018).

3.4.3 AGRICULTURE DEVELOPMENT ON PEATLANDS – IMPLICATIONS

Tropical peatlands exemplify the competing demands of enhancing food security, mitigating climate change, improving resilience and supporting rural livelihoods (Lupascu *et al.*, 2023). Innovations like paludiculture and water-table management are being promoted to mitigate emissions by reducing drainage and preserving soil moisture, which reduces carbon release. Paludiculture is proposed as a sustainable, non-drainage-based agriculture alternative for peatland use, which targets biomass production on wet peatlands with the potential to maintain carbon storage. This concept was initially developed in temperate ecoregions, but it is increasingly being used in tropical regions to minimize peatland loss while still allowing some production function. Agroforestry and crop selection for wet-adapted species are additional strategies that minimize the carbon impact of agricultural use on peatlands.

Even with these sustainable practices, agricultural peatlands often continue to emit CO_2 at higher rates than undisturbed peatlands. Paludiculture, for example, reduces but does not eliminate emissions, as minor drainage is still needed for crop cultivation. There is some limited evidence suggesting that paludiculture would generally result in lower agricultural profitability than conventional agriculture under current economic scenarios, so may not be a fully viable option immediately (Mulholland *et al.*, 2020; Wichmann, 2017). With a favourable economic environment, including efficient carbon markets for emission reductions and sequestration and an adequate carbon price, such systems could play an important role in responsible peatland management (de Jong, 2020). Payments for ecosystem services, particularly related to water conservation and security, also offer a potential alternative finance mechanism for offsetting the opportunity costs of avoided drainage and agricultural development.

3.4.4 SUSTAINABLE MANAGEMENT OF PEATLANDS

Sustainable agricultural practices on peatlands show the potential to reduce emissions, but face critical limitations, particularly as climate change amplifies peatland vulnerability. Rising temperatures, variable rainfall and increased fire risk drive emissions from peatlands beyond agricultural controls, challenging even the most sustainable agricultural systems. Degraded peatlands can generally be restored to allow net carbon sequestration, but biodiversity, vegetation, hydrology and peat soil structure are not always fully restored, even after a decade of restoration efforts, as ecological processes occur over the long term. This can lead to weakened ecosystem resilience and severe degradation due to future disturbances. For example, fine fuel accumulation in young secondary vegetation can increase the risk of recurrent wildfires during dry periods, thereby preventing the development of mature ecosystems. As the recovery of degraded peatlands is fundamental to achieving net-zero goals and biodiversity targets, focused research and monitoring efforts are needed to further inform restoration investments and priorities.

High carbon losses from peatlands due to agricultural expansion and consequent degradation are documented in the scientific literature. However, the complexity of accurately measuring peatland emissions remains a challenge, as spatial heterogeneity and seasonal variations complicate emission modelling. Peatland restoration has been shown to reduce GHG emissions and promote biodiversity (Convention on Wetlands, 2021). Studies have demonstrated that rewetting peatlands can cut emissions and may be a good strategy in the long run, even taking into account the potential for increased CH_4 production in rewetted areas compared with drained peatlands (Günther *et al.*, 2020). While the Global Peatlands Initiative (2022) report calls for restoration efforts to meet 2030 emission-reduction targets, some scientific analyses highlight that successful peatland restoration may require decades to re-establish carbon neutrality, depending on the degradation level and peatland type (Günther *et al.*, 2020). This time lag underscores the need for an integrated policy approach in order to balance short-term and long-term climate goals.

An integral component of the sustainable management of peatlands is the effective and timely monitoring of the extent, conditions and functional structure of peatlands in natural, degraded and restored sites. The ability to conduct effective monitoring is often limited by gaps in technical capacity, adequate and advanced tools, skilled manpower and financial resources to maintain continuity. The integration of remote sensing and satellite data has improved monitoring of peatland health and land-use changes, with recent studies using ground-penetrating radar and light detection and ranging, combined with hyperspectral imaging, to assess peatland carbon stocks more precisely (Carless *et al.*, 2021). The various approaches used for monitoring peatland conditions and functions include plot-scale measurements for the degree of humification and stoichiometric ratio, and electromagnetic induction at the field to landscape scale for mapping peat thickness, subsidence rates, water table and peat moisture and identifying GHG emission hotspots (Minasny *et al.*, 2024). Traditional approaches to peatland monitoring include recurrent manual measurements in simple dip wells or automated measurements using piezometers. However, these also require considerable time and human resources for data collection and are often limited by accessibility and the need for a large number of monitoring points across extensive peatland areas.

In summary, sustainable agricultural practices on peatlands provide valuable tools for limiting emissions, but they are insufficient in and of themselves to prevent the impacts of climate change on peatland GHG release. An integrated approach that combines emissions-reducing agricultural practices with stringent conservation and restoration policies will be essential to addressing these dual challenges.

BOX 3.2. Managing peatlands

In adapting to and mitigating the effects of climate change, a few response options have immediate impacts, while others can take decades to deliver measurable results. Examples of response options with immediate impacts include the conservation of high-carbon ecosystems, such as peatlands, wetlands, mangroves and forests. Interestingly, peatlands and wetlands often contain organic soils (histosols), while forests contain mollisols (brown forest soils).

Organic soils (histosols) generally occur in peat and marshy lands. Peat consists of spongy materials derived from partially or fully decomposed organic matter, primarily plant material, in wetlands such as swamps, bogs and moors. The colour of peat varies from dark brown to black depending upon its degree of decomposition. Peatlands cover around 423 Mha around the planet, accounting for about 2.8 percent of its total land surface area (Xu *et al.*, 2017).

Furthermore, the world's peatlands are located mainly in Asia (38 percent) and North America (32 percent), followed by Europe (12 percent) and South America (11 percent) (Xu *et al.*, 2017). The relative share of SOC stock at the global level indicates that these two types of soil reserve at least 20–25 percent of SOC. Peatland soils need conservation through appropriate management strategies. However, accurate estimates of the global extent of peatlands are uncertain, making the modelling of climate change impacts and climate feedbacks difficult. A recent study used machine learning techniques and existing datasets to develop a spatially continuous global map of peatland coverage (Peat-ML), which can be used in earth system models (Melton *et al.*, 2022).

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4. Crops

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4.1. IMPROVED CROPS INCLUDING GENE TECHNOLOGY

4.1.1 INCREASING CROP PHOTOSYNTHETIC EFFICIENCY

The ratio of chemical energy gained in the form of crop biomass to light energy absorbed, even in the most productive crops, falls well short of the theoretical thermodynamic efficiency of photosynthesis (Zhu, Long and Ort, 2010). This realization has motivated efforts to engineer improved efficiency in crops, including the adaptation of photosynthesis to future conditions. As photosynthesis involves more than 100 proteins and many more genes, it was previously difficult to determine where to intervene. High-performance computing, however, has allowed the development of digital twins that have guided interventions, largely by up-regulating the expression of specific genes (Wang, Chan and Long, 2021; Croce *et al.*, 2024; Khan *et al.*, 2024; Vijayakumar *et al.*, 2024). These computational predictions have been validated in single-location field trials of different transgenics that have shown significantly improved yields of 15 percent to 30 percent, higher water-use efficiency (WUE) and the future-proofing of photosynthesis to rising CO_2 concentrations and temperatures, where WUE is the ratio of CO_2 absorbed per unit of water used by the crop (Yoon *et al.*, 2020; De Souza *et al.*, 2022; Raines, 2022; Meacham-Hensold *et al.*, 2024; Salesse-Smith *et al.*, 2025; Salesse-Smith, Wang and Long, 2025). Many of these improvements have addressed limitations to both photosynthesis and WUE caused by the rapid rise in CO_2 concentration (Long, 2025). These have largely involved the transgenic up-regulation of genes the crop already has. Even in countries that accept transgenic crops, it is a long pathway to providing these advances to farmers. Up-regulation can now be achieved by editing the non-coding upstream region of genes (Tena, 2024). Many countries have introduced guidelines that allow such edited lines in a similar way to conventionally bred lines (Buchholzer and Frommer, 2023), creating the opportunity for faster deployment of these advances to seed systems and farmers.

4.1.2 RISING ATMOSPHERIC CARBON DIOXIDE CONCENTRATION – DIRECT EFFECTS

In the absence of stress, the yields of C3 crops — elite cultivars of rice and soybean — increase by about 30 percent with the elevation of CO_2 to anticipated 2050–2060 levels. C4 crops, including maize and sorghum, do not show a yield increase, as they are already CO_2 saturated. However, in drought, the yields of both C3 and C4 crops can be increased, as stomata show reduced conductance in elevated CO_2 concentrations, resulting in better conservation of soil water (Ainsworth and Long, 2020). Yet, in years when soil moisture is high during establishment, elevated CO_2 concentration can lead to poorer root development than at current CO_2 concentrations, impacting yield if soil moisture is depleted later in the growing season. This may be because elevated CO_2 concentration suppresses transpiration, and with lower demand for soil moisture during early development, there is less demand for investment in roots. Seed and grain quality is generally depressed, particularly the protein content of non-legumes, for a variety of reasons. Increased leaf carbohydrate levels suppress the expression of photosynthetic genes, in particular, ribulose-1:5-bisphosphate carboxylase (Rubisco), lowering a key supply of nitrogen from leaves during grain filling. Reduced transpiration lowers the content of nutrients that are transported to the shoot in the xylem stream, such as calcium and zinc. There is wide variation in protein and mineral content within the germplasm of the major food crops, suggesting that breeding could address quality loss (Ainsworth and Long, 2020).

4.1.3 TEMPERATURE INCREASE

Rising average temperatures and frequency of extreme temperature events are predicted to reduce production, especially in warm climates. Temperatures of 10 °C above optimum levels for photosynthesis (25 °C for C3 and 35 °C for C4) result in a sharp loss of CO_2 assimilation. This is attributed to the lability of Rubisco activase, the regulatory protein of the primary carboxylase of photosynthesis, Rubisco. The recent development of high-throughput assay methods has shown considerable variation in Rubisco activase temperature tolerance within the germplasm of major crops. Single amino acid residue changes, which improve thermal stability, have also been identified (Degen, Worrall and Carmo-Silva, 2020; Amaral, Lobo and Carmo-Silva, 2024). Both advances suggest means to future-proof photosynthesis against temperature increase.

Optimum temperatures for reproductive development in most crops are substantially lower than in vegetative development. High temperatures lower pollen viability and tube development, slow cell division rates in seed and fruit development, and shorten the grain-filling window (Long, 2025). Significant variation in the effect of high temperatures on pollen viability and tube development was found in a survey of just 44 soybean genotypes (Salem *et al.*, 2007). This suggests that with a wider search of germplasm, including the wild ancestor Glycine soja, the distribution of which extends from Siberia to subtropical China (Li *et al.*, 2024), better tolerance could be found. Large genotypic variations in heat tolerance of a percentage of filled grains, pollen production, pollen shed and pollen viability were found in 21 rice genotypes/ecotypes for heat tolerance, with greater heat tolerance in upland genotypes (Long, 2025). A survey of 304 diverse elite winter wheats showed significant variation in heat-stress tolerance of grain filling, identifying lines for breeding future-proofed wheat (Fu *et al.*, 2023). These all suggest considerable scope for improving the heat tolerance of these major food crops.

4.1.4 DROUGHT AND WATER-USE EFFICIENCY

Predicted increases in future precipitation are more than offset by increased run-off and evapotranspiration, leading to about a 25 percent increase in crop losses due to drought (FAO, 2021; Hasegawa *et al.*, 2021; Vicente-Serrano *et al.*, 2024; Long, 2025). Extensive research efforts have been dedicated to identifying drought tolerance genes in the model plant Arabidopsis, yet their successful integration into commercial crops remains limited (Martignago *et al.*, 2020; Zhang, Zhao and Zhu, 2020; Xu, D.R. *et al.*, 2023). The introduction of the Bacillus subtilis cold shock protein B, which downregulates ethylene production, into maize has improved drought tolerance and yield. Two years of trials in Nigeria showed a significant yield increase under moderate drought conditions (Oyekunle *et al.*, 2023). Improving WUE to lower the rate of depletion of soil water is another means of protecting against drought. With 40 percent of crop production on irrigated land, accounting for 71 percent of global freshwater withdrawals (Richter and Roser, 2024), improved WUE will be vital in enabling further production increases. Overexpression of Photosystem II Subunit S lowered stomatal conductance at all light levels, but did not affect CO_2 assimilation, resulting in a 15 percent improvement in leaf-level WUE and a 30 percent decrease in whole-plant water use in tobacco (Głowacka *et al.*, 2018; Turc *et al.*, 2024). Moderate reductions (less than 50 percent) in stomatal density by the transgenic expression of epidermal patterning factor genes in rice, wheat and sorghum improved WUE by around 15—20 percent without affecting yield (Caine *et al.*, 2019; Dunn *et al.*, 2019; Ferguson *et al.*, 2024).

4.1.5 FLOODING

After drought, flooding is the second-largest cause of global crop losses, at 19 percent (FAO, 2021). The major impact of flooding is that it prevents oxygen from reaching crop roots. Marsh plants and rice avoid this problem by the presence of large air channels that permeate their roots, allowing the diffusion of oxygen from the shoot. A survey of the root anatomy of 256 different maize cultivars and relatives revealed germplasm in which similar air channels are present (Burton, Brown and Lynch, 2013). Understanding of the molecular basis of adaptive plant responses to soil hypoxia has advanced significantly in recent years (Sasidharan *et al.*, 2017, Reynoso *et al.*, 2019, Schneider *et al.*, 2023), creating an opportunity to up-regulate these responses to protect roots during flooding. This does not help if flooding is so severe that the shoot is also submerged and starved of oxygen. Of land planted to rice, 35 percent is prone to floods that can submerge the developing crop for days. Surveying the ability of rice cultivars to survive up to two weeks of complete submergence, a tolerant cultivar was discovered and associated with allele Sub1A-1 at the Submergence 1 locus. This gene is rapidly induced on submergence, protecting the plant from damage. Subsequent introgression of Sub1A-1 into flooding-intolerant cultivars made them flooding tolerant (Emerick and Ronald, 2019). This discovery allowed the marker-assisted introgression of Sub1A-1 into a wide range of germplasm, aiding poor farmers in the most flood-prone areas, who rapidly adopted the flood-tolerant lines (Mackill *et al.*, 2012).

4.1.6 CROP SYSTEMS AS CARBON SINKS

Crops can have a dual role in both food security and climate change mitigation. There are major opportunities to make crop systems part of the solution to climate change. No-till has begun to slowly reverse the losses of soil carbon from earlier deep-tillage practices (Bernacchi, Hollinger and Meyers, 2005; Chi *et al.*, 2016; Kan *et al.*, 2022). Recent work shows that such soil carbon sequestration could be enhanced by the use of cover crops (Poeplau and Don, 2015), as well as by soil silicate applications. The application of silicate is viable at scale and found to also lower soil nitrogen oxide emissions while increasing yields (Horton *et al.*, 2021; Chiaravalloti *et al.*, 2023; Kantola *et al.*, 2023; Beerling *et al.*, 2024). The top four crops in terms of global seed/grain production are wheat, rice, maize and soy, which occupy almost 1 billion ha of the world's surface (FAOSTAT, 2024). About 50 percent of the biomass of these crops (around 2 $GtCO_2e$) remains, or could remain, on or in the soil after harvest. If the decomposition of this residue was slowed, soil carbon storage would rise. There are known means to bioengineer or breed cell walls to be more recalcitrant. Deeper root systems would also increase soil carbon storage (Eckardt *et al.*, 2023; Long, 2025).

Afforestation is a widely adopted means of offsetting carbon emissions. Forests, in their aggradation stage, can sequester between 1 tCO_2/yr and 35 tCO_2/yr into new biomass (Nabuurs *et al.*, 2007). A mature crop of the perennial C4 grass, Miscanthus x giganteus (miscanthus), grown in Illinois, sequestered 130 tCO_2/yr (Dohleman *et al.*, 2012). As productive as this may seem, plant breeders have identified substantially more productive miscanthus genotypes (Njuguna *et al.*, 2023). Miscanthus, in common with other highly productive C4 perennial grasses, such as switchgrass (Panicum virgatum) and energy cane (Saccharum hybrids), produce an annual crop of shoots from perennating rhizomes or stem bases. Selecting the most productive of these three crops for each gridded location of the marginal land of the eastern United States could capture 600 $MtCO_2$ into harvestable shoot biomass (He *et al.*, 2024). The alteration of surface albedo and evapotranspiration by such planting would also lower regional summer temperatures by 1 °C, so providing broader environmental benefits (He *et al.*, 2022). Used in conjunction with bioenergy carbon capture and storage (BECCS) and the expanding CO_2 pipeline network, such cropping systems could serve as major CO_2 collectors (He *et al.*, 2024; Minervini *et al.*, 2024).

4.1.7 BOTTLENECK IN PLANT BREEDING

The previous sections have highlighted many opportunities to increase productivity, adapt and improve resilience to climate events, remove atmospheric CO_2 and future-proof crops. Realizing this will require the introgression of transgenes, edits and advantageous alleles into locally adapted elite germplasm. Capacity to do this, especially where most needed, is seriously lacking. The last four decades have seen a sharp decline in public plant breeding, offset to some extent by the ascendency of a few multinational companies with vast plant-breeding capability (Brush, 2009; Coe *et al.*, 2020). Most of this multinational investment is necessarily focused on short-term financial gain and, in particular, North American maize improvement (USDA ERS, 2025). Nevertheless, the near doubling of US maize yields over the last 45 years (Long, 2025), shows what can be achieved with adequate human and technical resources. Such levels of investment in training, people and technology are urgently needed, especially for the staple crops of the regions most at risk of food shortages. Equally, ensuring that farmers in these regions have access to agronomic advice and adequate fertilizer is essential if an increase in global hunger is to be averted. This will require realism in what can be done with limited resources, by focusing effort on the most productive staples for a region and likely placing production ahead of sustainability. Besides starvation, failure to increase production on existing agricultural land will inevitably motivate expansion into more natural habitat, particularly tropical forest, to the continued detriment of biodiversity and carbon emissions.

4.2. CROPS FOR BIOENERGY

4.2.1 CAN BIOENERGY CROPS BE A CLIMATE-FRIENDLY SOLUTION?

Fossil-fuel burning for energy generation, particularly in electricity production and transportation, is the world's largest source of GHG emissions, followed by agriculture and land-use change (IPCC, 2021). Using bioenergy crops to produce biofuels is a well-established strategy for energy transition, offering the potential to reduce reliance on fossil fuels, decrease GHG emissions and enhance energy security (IEA, 2023).

Bioenergy crops include a range of food crops (namely, maize, sugarcane, sugarbeet, wheat and soybean) and non-food crops (such as miscanthus, switchgrass, energy cane and other perennial crops). Traditional food crops (such as grains, oilseeds and sugar crops) remain the most widely used bioenergy sources worldwide. Well-established cultivation practices, a dual purpose for food and bioenergy, mature processing technologies, existing infrastructure and the accumulated expertise of both farmers and industry professionals underpin their extensive use. In contrast, recent studies (for example, Næsss *et al.*, 2022) indicate that perennial bioenergy crops could be more sustainable due to their lower environmental impact and reduced competition for land.

The heavy reliance on conventional food crops for bioenergy raises several concerns. Their expansion can lead to competition with food production, deforestation and the conversion of natural ecosystems, contributing to biodiversity loss and disrupting ecosystem services. Intensive cultivation of these crops may also drive up food prices, worsen food insecurity in vulnerable regions and result in net reductions in soil carbon stocks, thereby undermining climate change mitigation efforts (Mello *et al.*, 2014; Smith *et al.*, 2019; Winberg *et al.*, 2023).

To mitigate the negative impacts associated with land-use change, recent research advocates for expanding bioenergy crops onto marginal lands and to areas with some degree of degradation (Cherubin *et al.*, 2021a; Vera *et al.*, 2022). These sites, which are less productive for conventional agriculture, offer the dual advantage of reducing competition with food production while potentially restoring ecosystem services, such as increased soil carbon sequestration (Khanna *et al.*, 2021; Oliveira *et al.*, 2017). In this context, marginal lands have been identified as the most economically and environmentally viable option for sustainable bioenergy expansion in the northern hemisphere (Khanna *et al.*, 2021; Næsss *et al.*, 2022). Similarly, around 100 Mha of degraded pasture have been recognized as priority areas for bioenergy development and expansion in Brazilian territory (MapBiomas, 2024; Cherubin *et al.*, 2021a). A major challenge remains the lack of a clear and universally accepted definition of marginal or degraded lands, which poses significant challenges for policy implementation and land-use planning. The classification of land as marginal or degraded is inherently subjective, varying with context due to the complex interplay of biophysical factors (such as soil type, topography and climatic conditions) and management practices (including agricultural methods and land-use history). The absence of standardized criteria for assessing land degradation further complicates the matter, leading to inconsistent interpretations that hinder effective planning and the development of coherent policies for bioenergy expansion.

Furthermore, it is essential to avoid expanding into environmentally sensitive areas, such as regions near water bodies and biodiversity or carbon storage hotspots, irrespective of their state of degradation, as doing so can result in habitat destruction, water pollution and the release of stored carbon, ultimately undermining conservation efforts and climate change mitigation goals (Hernandes *et al.*, 2021).

4.2.2 CAN THE INCLUSION OF A SECOND CROP BE A VIABLE STRATEGY TO SUPPORT BIOENERGY EXPANSION?

Integrating bioenergy crops as a second cash crop or cover crop in existing agricultural areas has emerged as a prominent solution for sustainable bioenergy expansion without undesirable land-use impacts (Moreira *et al.*, 2020; Taheripour *et al.*, 2022; Gurgel *et al.*, 2024). These crops (such as maize, sunn hemp, camelina and carinata) can be produced on existing cropland areas in a multi-cropping system, increasing the yield per unit of land, improving soil health and boosting soil carbon sequestration. In the United States and Europe, oilseed cover crops, such as camelina and carinata, have recently been proposed for biofuel production, as they avoid land-use side-effects (Taheripour *et al.*, 2022). They are more efficient in producing biofuels, more resilient to climate effects and require fewer agronomic inputs than traditional crops.

Moreira *et al.* (2020) note that agricultural intensification through second-crop maize in traditional soybean areas is a practical strategy for producing bioethanol with a low-carbon footprint and without adverse land-use effects. The production of second-crop maize in soybean areas in Brazil has increased from 13 Mt to 102 Mt over the past two decades (CONAB, 2024). Several factors, including growing demand in the maize ethanol industry, government policy and market prices are behind this expansion. Recently, second-crop maize production has become an important feedstock for biofuel production, accounting for 20 percent of the country's bioethanol production in 2023. In a recent study, Gurgel *et al.* (2024) concluded that the production of second-cropping maize in central-western Brazil was environmentally and socially beneficial to producing food/feed and biofuels compared with the status quo. Expanding second crops in traditional rotation schemes not only produces biofuel, but also co-products, such as dried distiller grain and maize stover, which can be used for animal feed or bioelectricity production (Moreira *et al.*, 2020). Using maize co-products for animal feed might reduce the direct need for land for livestock production and indirectly reduce the pressure for deforestation.

While the production of second crops and best use of agro-industry residues may reduce deforestation pressure, it is important to consider the possibility of indirect land-use change. Indirect land-use changes occurs when intensifying production in one area displaces agricultural activities in other regions. The indirect land-use change concept has been much discussed in recent decades (see, for example, Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Zilberman 2017) and is now a clearly defined concept used in IPCC work (IPCC, 2019). Indirect land-use change evaluations have frequently been used in bioenergy production systems worldwide.

4.2.3 CAN THE VALORIZATION OF BIOENERGY CO-PRODUCTS BE A GAME-CHANGER?

Bioenergy crops are often efficient at temporarily removing CO_2 from the atmosphere through photosynthesis, but this carbon is released back into the atmosphere when the biomass is used for energy production. Harvesting and converting biomass into bioenergy products generate residues (or co-products), and the ultimate destination of these residues determines the cost effectiveness and sustainability of the bioenergy.

The appropriate use of residues can increase the overall efficiency and sustainability of bioenergy production systems. In some cases, the amount of residues is higher than the main bioenergy products. For example, each litre of sugarcane ethanol produces around 13 litres of vinasse, a liquid residue produced from ethanol distillation, which is primarily applied to fields to recycle nutrients and improve soil health (Luz *et al.*, 2024). Vinasse could also be used for the production of biogas and biomethane, increasing the amount of bioenergy per unit of biomass produced in the field (Moraes *et al.*, 2014; Longati *et al.*, 2020). In the same way, sugarcane lignocellulosic biomasses (bagasse and straw) can also be used to produce bioelectricity and cellulosic ethanol. However, it is important to emphasize that care should be taken when removing lignocellulosic biomass from the soil surface. The indiscriminate removal of crop residues from agricultural soils can come at an environmental cost (Bordonal *et al.*, 2024), reducing soil carbon stocks (Karlen *et al.*, 2019; Xu *et al.*, 2019; Tenelli *et al.*, 2021) and soil health (Cherubin *et al.*, 2021b). Globally, it is recommended to retain at least 30 percent of crop residues on the soil surface to maintain soil health and prevent erosion (Cherubin *et al.*, 2021b; Gallo *et al.*, 2023; Corsi and Muminjanov, 2019; Tittonell, 2014). Therefore, it is essential to balance the utilization of crop residues for bioenergy production with the need to maintain soil health and ecosystem services. The results presented here illustrate the impact of co-product valorization on bioenergy crops in a biorefinery and can be replicated for some bioenergy crops.

The effectiveness of bioenergy in mitigating climate change depends on multiple factors, including land-use changes, the efficient use of residues and the adoption of carbon removal technologies. Research suggests that bioenergy products can effectively mitigate GHG emissions (Carvalho *et al.*, 2021; Xu *et al.*, 2022). However, by themselves, bioenergy crops are insufficient to decarbonize the energy system. To produce bioenergy with zero or negative GHG emissions, the bioenergy system must go hand in hand with the adoption of CDR technologies (IPCC, 2022), such as BECCS and biochar (Næss *et al.*, 2022; Lefebvre *et al.*, 2023; Silveira, Costa and Santos, 2023; Buffi *et al.*, 2024; Gurgel *et al.*, 2024; Hayat, Alhadhrami and Elshurafa, 2024).

BECCS technology captures CO_2 emitted from biomass combustion in boilers and ethanol fermentation, and stores it in geological formations, where it is retained for thousands of years (IPCC, 2022). Biochar's CDR potential lies in its ability to stabilize CO_2 absorbed by plants through photosynthesis. During pyrolysis, this biogenic CO_2 is converted into a stable carbon form (Lehmann and Joseph, 2021). The pyrolysis process thermochemically transforms biomass into bio-oil, biochar and syngas. Syngas is used for heat production, bio-oil for biorenewables production, and biochar is applied to soils for long-term soil carbon sequestration.

It is important to highlight that biochar and BECCS do not compete for carbon sources and can be used together in the same industry (Buss *et al.*, 2019). Biochar can be produced from lignocellulosic residues, while BECCS can be implemented by using CO_2 produced in boilers and/or fermentation processes. Beyond soil carbon sequestration, some CDR technologies, such as biochar, can deliver several co-benefits, including increased soil health and crop yields (Blanco-Canqui, 2021). Other CDR technologies, such as direct air carbon capture and storage and enhanced weathering, are currently at a lower technological readiness level (IPCC, 2022), but could also be integrated into the bioenergy sector.

Replacing fossil fuels with bioenergy is an ally in the fight against climate change. However, its effectiveness in reducing GHG emissions depends on several factors related to land expansion, crop yield and converting "whole" biomass into bioenergy. Optimizing the use of agroindustrial residues can directly impact the amount of bioenergy produced per unit of biomass, affecting the sustainability of the bioenergy chains. Lastly, more studies are needed on the adoption of CDR technologies in current bioenergy chains.

4.3. RICE VARIETIES AND MANAGEMENT FOR LOW GREENHOUSE GAS EMISSIONS

Rice cultivation is considered a major anthropogenic source of CH_4 and N_2O emissions, accounting for about 48 percent of total GHG emissions from croplands, of which CH_4 makes up a significant portion (Qian *et al.*, 2023). CH_4 is emitted into the atmosphere by several means: diffused from water or soil, released as gas bubbles, and transported through plants into roots, where it is converted into CH_4 gas and released through micropores (Davamani, Parameswari and Arulmani, 2020). Focusing on mitigation and adaptation strategies has become essential to sustaining rice production and guaranteeing food security. Rice varieties that emit low levels of CH_4 and exhibit greater resource-use efficiency have been researched with a view to reducing GHG emissions from paddy soils (Hussain *et al.*, 2015) (Section 4.3.1.). Moreover, different management approaches, such as alternate wetting and drying, adjusting tillage methods, managing organic and fertilizer applications, and altering crop patterns have been recommended to reduce GHG emissions in rice (Hussain *et al.*, 2015, 2020) (Section 4.3.2).

4.3.1 RICE VARIETIES FOR LOW EMISSIONS

Several recent research studies conducted under various environmental conditions have shown the differences between rice types and varieties when it comes to CH_4 emissions (Feng *et al.*, 2021; Martínez-Eixarch *et al.*, 2021; Hu *et al.*, 2023; Zhang *et al.*, 2023; Wang C. *et al.*, 2024). Variations in CH_4 emissions among rice varieties have been attributed to differences in their CH_4

production, oxidation and transport abilities (Zhang *et al.*, 2023). Nonetheless, during the rice cultivation period, the highest amount of CH_4 generated in the soil is emitted through diffusive transport, via the aerenchyma system, rather than diffusion or ebullition (Gupta *et al.*, 2021). Zhang *et al.* (2023) noted that variations in above-ground and below-ground biomass, the root's ability to release oxygen and the gas transport capacity of aerenchyma in various rice varieties could result in marked differences in total CH_4 emissions. Cultivars that emitted less CH_4 exhibited significantly reduced gas transport abilities in their aerenchyma systems than other cultivars. Therefore, identifying and using high-yield rice varieties with lower gas transport abilities provides an economical and environmentally sustainable strategy for reducing methane emissions in rice paddy fields (Chen *et al.*, 2024).

Efforts have also been made to develop advanced rice varieties with vigorous growth and efficient root systems in order to reduce GHG emissions and improve productivity, resource-use efficiency and climate resilience. Research indicates that increasing biomass in high-yielding varieties of rice reduces CH_4 emissions from paddy soils by enhancing carbon sequestration and minimizing carbon footprints (Jiang *et al.*, 2017; Grotto *et al.*, 2020). Rice varieties that possess a more robust root system and increased root exudation demonstrate greater root oxidation activity, release more oxygen into the soil, enhance root porosity and improve abiotic stress tolerance, as well as crop yield (Zhang *et al.*, 2019). This enhanced oxygenation transforms SOC into CO_2 rather than CH_4, reducing CH_4 emissions (Ishfaq *et al.*, 2020). New rice varieties that allocate more photosynthates to the seeds may decrease the photosynthate allocation below ground for methanogens, thereby reducing CH_4 emissions (Feng *et al.*, 2021). Likewise, selecting rice varieties with effective absorption and use of nitrogen fertilizer lowers ammonia (NH3) emissions (Yang *et al.*, 2022), although data on NH3 fluxes in wetland rice ecosystems are still relatively scarce (Uddin *et al.*, 2021).

Water-saving and drought-resistant rice (WDR) varieties with dry cultivation have been reported to lower GHG emissions and yield-scaled GWP from paddies (Zhang *et al.*, 2021). These WDR varieties can decrease CH_4 and N_2O emissions by 8—100 percent and 7—76 percent, respectively, while also reducing GWP by 11–95 percent (Feng *et al.*, 2021; Habib *et al.*, 2023; Zhang *et al.*, 2023). This could be attributed to WDR varieties' enhanced ability to absorb water and reduced water requirements. To create WDR varieties, it is essential to enhance the key traits of yield potential, drought resistance and WUE in the breeding process. Some researchers also report that drought-tolerant varieties that perform better under alternate wetting and drying can significantly reduce CH_4 emissions throughout the growth period (Martínez-Eixarch *et al.*, 2021; Wang *et al.*, 2024). Moreover, the cultivation time is also linked with GHG emission and its mitigation in rice. Belenguer-Manzanedo *et al.* (2022) suggest that a shorter season is the key factor when selecting low-emission varieties, due to a reduction in flooding time. Consequently, future breeding programmes should aim to develop rice varieties that are climate resilient, short duration and capable of minimizing GHG emissions while maintaining high yield levels. The principal varietal characteristics identified by the aforementioned studies for GHG emissions include biomass accumulation, root traits, amount of root exudates, accumulation of photosynthates in grain, crop growth duration and crop phenology.

In essence, innovative and sustainable techniques, such as water-efficient irrigation, direct sowing, advanced breeding practices and carbon credit schemes, should be chosen to enhance the effectiveness of rice varieties in reducing GHG emissions. Nonetheless, the impact of different rice varieties combined with various agronomic practices on CH_4 emissions requires further investigation. This void needs to be addressed to demonstrate the efficacy of employing certain high-yielding varieties to lower CH_4 emissions and to further explore the traits that lead to lower emissions. A comprehensive approach that includes better irrigation systems, consistent monitoring and engagement with stakeholders is necessary to attain significant reductions in emissions and ensure food security. Integrating these elements will enhance the sustainability and resilience of rice farming in response to climate change.

4.3.2 RICE MANAGEMENT FOR GHG EMISSION REDUCTIONS

Some 18 percent of all CH_4 is emitted from rice paddy fields (Hussain *et al.*, 2020). Consequently, mitigation and adaptation strategies are needed. This may include alternate wetting and drying, intercropping with short-term vegetation, limiting chemical fertilizer by practising precision farming, using rice cultivars with low CH_4 emissions, high yields and abiotic stress tolerance (temperature, drought), improving tillage, recycling farm waste into organic fertilizers and developing integrated rice farming systems (Hussain *et al.*, 2020). In terms of mitigation potential, a recent review concluded that integrated agronomic management strategies — including cultivars, organic matter, water, tillage and nitrogen management — offer GHG mitigation potential (Qian *et al.* 2023). In particular, multiple studies have shown that new rice variety selection, non-continuous flooding, straw removal strategies and biochar can reduce GHG emissions by 24 percent (under high levels of SOC), 44 percent (with single and multiple drying events), 46 percent and 13 percent (of CH_4), respectively, on average (Qian *et al.*, 2023), but also contribute to climate adaptation.

However, changes to existing management practices can simultaneously influence more than one gas (CH_4, N_2O) and their effects may be opposite. Ahmed *et al.* (2022) found that modifying irrigation and tillage practices, improving fertilizer management, using low-emitting rice varieties, incorporating fermented cow dung and leaf manures, adding nitrification inhibitors and applying slow-release fertilizers manifested great potential to abate CH_4 and N_2O emissions. The incorporation of biochar, straw compost and straw ash may have better results in curtailing GHG emissions than direct straw additions (Ahmed *et al.*, 2022). Similarly, non-continuous flooding can increase N_2O emissions, although these increments generally do not offset the benefit of reduced CH_4 emissions (Qian *et al.*, 2023).

4.4. AIR POLLUTION CLIMATE INTERACTIONS – IMPACTS ON CROP PRODUCTIVITY

There is growing awareness and understanding of how air pollution (predominantly tropospheric ozone, aerosol and nitrogen species) and climate change (primarily related to CO_2 fertilization, changes in temperature and precipitation) interact to affect agricultural (mainly arable) productivity (Sillmann *et al.*, 2021; Fischer, 2019;; Shindell *et al.*, 2019; Leung *et al.*, 2022). Many studies have attempted to assess the relative contributions to damage of these different factors, either globally (Shindell *et al.*, 2019) or by global region (for example, Asia Pacific [UNEP, 2018] and Africa [UNEP, 2022]). Findings suggest that the importance of different factors on crop productivity can vary substantially and are dependant on the time frame being considered, as changes in climate that will substantially affect agriculture may only be realized after decades, while air pollution impacts (where concentrations are already high) are occurring now. South and East Asian regions are being increasingly investigated because of their high pollution loads.

Extreme drought and heat stress, ozone stress and aerosol-induced decreases in radiation are causing declines in crop productivity, while CO_2 fertilization, nitrogen deposition and aerosol-induced increases in diffuse radiation, along with instances where climate change creates closer-to-optimum conditions for crop growth, can actually improve yields.

Actual changes in crop productivity due to air pollution—climate change interactions depend on the local/regional conditions on which air pollution and climate change can have an effect, and how these are likely to change over time. For example, in China, nitrogen deposition was found to have both advantages — through fertilization and the cooling effect of aerosols — and disadvantages — as a result of excessive nitrogen deposition reducing crop yields by increasing crop water demand and contributing to greater GHG emissions, leading to climate change (Zhang, Zhang and Zhou, 2024). The critical role that aerosol and ozone pollution play in determining crop yields was also found to vary by time period (Wang, 2021). Aerosol pollution mitigation reduced the negative impacts of concurrent climate change in the short term, despite ozone increases in the North China Plain, but the impacts of climate change, particularly from surface temperature increase, were more weighty than pollution factors in the longer term (He *et al.*, 2022). Interactions between ozone and drought across Europe had bigger effects on wheat yield than when the two stresses were applied separately (Nguyen *et al.*, 2024). Similarly, the tendency for high ozone concentrations to coincide with hot summers and heatwaves was found to be a cause for concern in the wine-growing regions of Portugal (Ascenso *et al.*, 2021).

Studies considering the effects of air pollution and climate change on arable crops have tended to focus on productivity (for example, grain yield), but more recently, the combined adverse effect of air pollution and climate change on the nutritional quality of crops has become evident. Increased CO_2 has been found to enhance heavy-metal loads in crops (through uptake from the soil), reducing crop nutritional status, particularly in cereals (Yang *et al.*, 2024) and rice (Yang *et al.*, 2023). Ozone and climate change have also been found to affect nutritional status (Cook *et al.*, 2024).

Studies tend to focus on four key staple crops (wheat, maize, rice and soybean) and be based on experimental data from North America, Europe and, more recently, Asia. However, new crops and regions are now being explored, perhaps most notably African crop varieties (wheat, finger millet, pearl millet and bean) (Hayes *et al.*, 2019; Sharps *et al.*, 2021). Hayes *et al.* (2019) found differences in sensitivity to ozone for different cultivars of individual crops (wheat and beans), indicating that there could be possibilities for either cultivar selection or selective crop breeding to reduce the sensitivity of these crops to ozone. This becomes important, as African regions are predicted to see an increase in surface mean ozone concentrations due to projected changes in climate (Racherla and Adams, 2006).

Assessments of the combined effects of air pollution and climate change also depend on the risk-assessment method used in the study. Methods that can account for climate-induced sensitivity of crops to air pollution are most useful and can return interesting results. For example, the use of a flux-based approach in a study in Taiwan allowed separation into ozone-induced and climate-induced effects. The former dominated the additional yield reduction under a 2 °C warming climate, yet the latter prevailed under 4 °C warming, with vapour-pressure deficit and solar radiation also playing a role in determining ozone sensitivity (Tsai *et al.*, 2022).

There is also a growing body of evidence describing interactions of air pollution with biotic stresses that are likely to be altered by climate change. Ozone interactions with yellow rust have been found to be beneficial for wheat in the Mediterranean region, with current ozone concentrations protecting cereals against yellow rust formation by around 22 percent more than pre-industrial ozone levels (Chang-Espino *et al.*, 2023). This suggests the need to consider breeding more resilient varieties to such abiotic stresses if ozone levels are reduced as a by-product of GHG mitigation. The mechanisms of the shift in plants' competitiveness in response to single and combined environmental changes (such as elevated CO_2, increased temperature and ozone) in summer rape and wild mustard suggest potential increased weed-induced yield losses under future climate scenarios (800 µmol/molCO_2, 25 °C/18 °C day/night temperature), particularly when combined with higher ozone pollution (Kacienė *et al.*, 2019).

It is also worth noting that crop production causes emissions that lead to air pollution and climate change (IPCC, 2019). Ammonia emissions associated with manure and fertilizer treatments have remained stubbornly high (Pastorino *et al.*, 2024), in part due to demand for food and feed crops. These emissions can lead to secondary aerosol formation which can, in turn, impact crop productivity, either positively or negatively, by altering light and temperature levels (Liu and Desai, 2021). Similarly, agricultural residue burning is increasingly regarded as a substantial contributor to high aerosol loads, particularly across parts of Asia. Measures to reduce burning from agriculture are increasingly being considered (Divyabharathi *et al.*, 2024).

Optimizing the abatement of such agricultural emissions requires integrated air pollution and climate change approaches due to the feedbacks, benefits and trade-offs involved. For example, a global integrated assessment of N_2O (UNEP and FAO, 2024) shows that abatement of N_2O emissions under a sustainable nitrogen management approach would significantly improve air quality through the concurrent abatement of NH3 and NOx emissions, which form fine particulate matter (PM2.5) and ground-level ozone. This would have multiple human health and crop benefits, as well as additional benefits for water quality, soil health and the structure and functioning of ecosystems. The reduction in NH3 and NOx emissions would, however, cause additional near-term warming, primarily due to the reduced cooling effect associated with lower aerosol concentrations in the atmosphere. However, because of the long lifetime of N_2O, the net effect of a sustainable nitrogen management approach would reduce warming in the longer term. It is, therefore, important that potential mitigation measures associated with crop production consider all air pollution and GHG outcomes simultaneously to design a balanced approach.

It is also useful to consider the geographic location of air pollution mitigation and the benefits this may have for local and regional climate and, hence, crop productivity. For example, Shindell *et al.* (2023) describe the important role of African emission reductions in projected local rainfall changes, an effect that had previously been attributed to the impact of aerosols outside Africa or the impact of global aerosols (Westervelt *et al.*, 2018; Liu *et al.*, 2018; Dong *et al.*, 2014; Undorf, Bollasina and Hegerl, 2018). Decarbonization strategies can often lead to a "climate penalty" when mitigation results in the simultaneous removal of cooling aerosols that offset the temperature benefits of CO_2 reductions. For precipitation, in contrast, the removal of cooling and warming aerosols can lead to avoided drying through decreased heating from reduced carbonaceous aerosols in the troposphere. Decreases in scattering aerosols and associated cloud cover can then lead to a greater short-wave flux reaching the surface, which can enhance land heating locally in parts of Africa, thereby contributing to increased rainfall. In Shindell *et al.*

(2023), this effect was particularly relevant for the Sahel region, which has suffered numerous droughts and is, therefore, an important area for further research.

Efforts are under way to assess and understand the effectiveness of all sectoral emissions mitigation on crop productivity (Von Schneidemesser *et al.*, 2020; Murray *et al.*, 2024; Shindell *et al.*, 2019). Exploring the effect of shared socioeconomic pathways (SSPs) and Representative Concentration Pathways (RCPs) on crop production from the present to 2090—2099, Murray *et al.* (2024) found that extreme mitigation scenarios (for example, SSP1—1.9) showed increases in food production due to ozone changes alone, while the most extreme warming scenarios (for example, SSP5—8.5) showed decreases in food production, particularly due to ozone-sensitive winter wheat. Importantly, all scenarios that aligned with the Paris Agreement gave net savings in crop production, although these were offset by the climate-driven increase in surface ozone over land (Murray *et al.*, 2024). In general, mitigation that tackles climate change through long-lived GHG reductions offers the greatest overall benefit in terms of improved crop productivity. However, aerosol-induced cooling may be important in India and China, and local benefits may be found by targeting specific pollutants (Shindell *et al.*, 2024). Other studies have focused on particular mitigation strategies, such as CH_4 in relation to global methane pledges (Sampedro *et al.*, 2023) and the effectiveness of regional rather than global mitigation strategies (Xu B. *et al.*, 2023). Studies have also started to explore the effect of geoengineering associated with changes in the quantity and quality of sunlight (Proctor, 2021). Cost-benefit analysis of mitigation has also explored broader contexts to include not only market-value economic losses, but also how economic losses fall disproportionately on different actors (for example, producers, consumers and government food welfare schemes) (Pande *et al.*, 2024), the effects on agricultural total factor productivity (Dong and Wang, 2023), and the evolution of cost-benefit ratios over time as mitigation pathways are deployed (Shindell *et al.*, 2021).

As well as mitigation, it is also important to consider adaptation of crop production to climate change and air pollution, which can be considered on a plant (genetic variation, molecular breeding, phenotyping), field (cultivation practices and technologies, mixed cropping and diversification) and ecosystem (modifying hydrology and microclimate of agricultural landscapes) scale (Agathokleous *et al.*, 2023). Understanding potential adaptation responses will be important, especially as studies such as Hansen *et al.* (2019) show evidence of greater ozone sensitivity among modern varieties of crops such as wheat, compared with older varieties.

The past few years have seen the development of both existing and new tools for crop impact assessment, allowing the combined effects of air pollution and climate change to be more readily understood. These include additional free-air concentration enrichment experimental facilities (Montes *et al.*, 2022), as well as new modelling approaches. The latter move on from the more traditional pollution-based exposure-response risk-assessment methods, which used flux-based approaches, allowing the incorporation of climate variables into pollution damage assessments (Silmann *et al.*, 2021; Wang *et al.*, 2023), to include crop models that incorporate ozone stress based on statistical models (Wu *et al.*, 2022; Mahmood, Khokhar and Mahmood, 2020), radiation-use efficiency models (Guarin *et al.*. 2024), or process-based crop models (Nguyen *et al.*, 2024). Crop models that can connect to meteorology—chemistry models are also now being developed (Wang X.Y. *et al.*, 2024; Pandey *et al.*, 2023; Lam *et al.*, 2023), along with machine learning frameworks (Du, Pei and Feng, 2024) and crop seasonal forecasting that includes air pollution (Banerjee and Mondal, 2024). These enable an integrated assessment of air pollution and climate change on crop productivity, which can more effectively inform mitigation and adaptation responses.

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5. Sustainable and integrated agricultural systems

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Climate-resilient agriculture is a farming system that has diverse environmental and socioeconomic potential, including: (i) increased crop productivity (Stavi *et al.*, 2016), (ii) decreased GHG emissions due to no-till and zero or little chemical fertilizer application (Araujo *et al.*, 2022; Shao *et al.*, 2025) and (iii) diversified sources of household income and livelihoods, as different crops and livestock and trees are grown together (Nwaogu and Cherubin, 2024). Thus, the system reduces land-use cover change-related stressors, as well as production risks and vulnerabilities, reinforcing both environmental sustainability and the resilience of rural communities (Zheng, Ma and He, 2024). This section considers recent studies in integrated agricultural systems (IAS), such as climate-smart agricultural systems.

What have we learned from Intergovernmental Panel on Climate Change reports to date?

- Efforts channelled into improving SOC sequestration through sustainable agriculture will promote carbon reduction in other sectors, as AFOLU (especially agriculture) is at the heart of other sectors (Nabuurs *et al.*, 2022).
- Global mitigation potential for soil carbon management in croplands is targeted at 1.9 (0.4–6.8) $GtCO_2e$/yr (FAO, 2023).
- Improved cropland nutrient management could mitigate 0.3 (0.06–0.7) $GtCO_2e$/yr between 2020 and 2050 (FAO, 2023).
- Agroforestry has been estimated to mitigate between 0.08 5.6 $GtCO_2e$/yr and 5.6 $GtCO_2e$/yr by 2050 (IPCC, 2019a; Hurlbert *et al.*, 2019).

5.1. WHAT NEEDS TO BE KNOWN ABOUT ADVANCES IN SUSTAINABLE AND INTEGRATED AGRICULTURAL SYSTEMS FOR CLIMATE CHANGE MITIGATION

Global carbon emissions have totalled about 136 GtC from soil exploitation and 270 GtC from fossil-fuel consumption since the industrial revolution (Chataut *et al.*, 2023). The SOC stock has declined by about 78 GtC as a result of anthropogenic activities (Bhattacharyya *et al.*, 2023). Together, land use and land-use change and the agricultural sector have been among the biggest emitters of GHGs, collectively responsible for 17–24 percent of global emissions (Stavi, 2023).

Climate-resilient agroforestry is expected to reduce the risks of crop failure due to drought and pest infestation, increase crop quantity and quality, diversify goods and commodities, improve the use efficiency of resources and lessen both the 'natural' and anthropogenic impact on the environment (Ntawuruhunga *et al.*, 2023). Generally, the benefits of agroforestry systems are derived from their diverse vegetation, multi-storied above-ground biomass and complex underground arena. The combined effects of these features include improving microclimatic conditions, providing habitats and refugia for (micro-, meso- and macro-) fauna, increasing soil fertility and quality, controlling the loss of water and soil resources, and reducing environmental contamination. Together, these effects decrease the overall anthropogenic impact on the environment, strengthen agroecosystem health by lessening the infestation of pests and diseases, support the delivery of functions and services, and improve the capacity of agroforestry systems to cope with climate extremes, such as severe droughts and intense rainstorms (Fahad *et al.*, 2022). Several types of agroforestry system are used, aimed at fulfilling a wide range of purposes. Different classifications of agroforestry exist, including that proposed in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019b). For example, silvopasture encompasses tree planting for restoring degraded rangelands by improving soil infiltrability and hydraulic conductivity (Stewart *et al.*, 2020), thus reducing soil erosion and nutrient loss, resulting in an increase in pasture productivity (Mackay-Smith *et al.*, 2021). Agrosilvipasture integrates trees with either food or feed crops on the same land, with a potential further increase in land profitability (Afentina *et al.*, 2021). Riparian buffers act as tree barriers between cropland and streams, reducing the loss of soil and water resources from cropland, while protecting the water quality of streams (Singh *et al.*, 2024). Hedgerows encompass tree buffers between adjacent cropland plots and are aimed at reducing hydrological connectivity, thus decreasing water overland flow and soil erosion (Yang *et al.*, 2019). Windbreaks encompass single to multiple tree lines along croplands borders and are aimed at reducing wind erosion (Chang *et al.*, 2021). Simultaneously, they also reduce soil-water evaporation rates, thus increasing WUE (Thevs, Aliev and Lleshi, 2021). Agrosilviculture, often designed as an alley cropping system, is used for the diversification of plant life forms, including trees, vegetables, cereals and legume crops, as well as for the restoration of degraded croplands (Montes *et al.*, 2019). Urban food forests are common in peri-urban or densely inhabited areas for the production of fruits and vegetables, alongside the delivery of several other benefits (Shi, 2023). Altogether, the worldwide areal cover of agroforestry systems is around 1 billion ha, operated by about 1.2 billion people (Ghale *et al.*, 2022).

These days, agroforestry has become an essential system that can be applied at any scale, especially in rural settings on degraded agricultural land, and it is associated with numerous environmental and socioeconomic sustainability benefits. According to Pandey *et al.* (2024), agroforestry is an agricultural system that encompasses the integration of perennial woody plants with crops or livestock and involves practices such as agrohorticulture, agropastoralism, agrosilviculture, agrosilvipasture and others. With a 12 percent global contribution to terrestrial carbon, agroecosystems are indispensable components of the global carbon cycle, presenting an option for remedial action to restore land degraded by some inadequate agricultural practices and forestry systems. Their vegetation and soils store about 2,000—2500 GtC, comprising 25 percent of global terrestrial carbon stocks (Pandey *et al.*, 2024), and agroforestry has a significant share of this large carbon pool. In line with the IPCC's third report, agroforestry guarantees several benefits for carbon sequestration that support the mitigation and adaptation of climate change (IPCC, 2001). Based on the IPCC's LULUCF assessment, agroforestry has been identified as the most efficient land use with regard to the rate of carbon stocks by 2040, exceeding other evaluated land uses (IPCC, 2000; Raj *et al.*, 2024).

The carbon storage in agroforestry systems can range from 29 tC/ha to 228 tC/ha, and agroforestry has the potential to remove 1.1–2.2 GtC from terrestrial ecosystems over the next 30 years (Raj *et al.*, 2021). In various agroecological regions, the carbon stock value of different agroforestry systems has been reported by Raj *et al.* (2024) as follows: agrosilvicultural systems in arid/semi-arid (lowland) regions (19.54 megagrams per ha per year [Mg/ha/yr]), agrosilvicultural systems in humid (lowland) regions (70.5 t/ha), agrosilvipastoral systems in arid/semi-arid (highland) regions (74.6 t/ha), silvopastoral systems in arid/semi-arid regions (91.82 t/ha), agrosilvipastoral systems in humid tropical regions (113.5 t/ha), silvopastoral systems in drylands (132.5 t/ha), silvopastoral systems in humid tropical lowlands (134.5 t/ha), silvopastoral systems in humid tropical highlands (143.5 t/ha), silvopastoral systems in tropical regions (152.5 t/ha) and silvopastoral systems in humid tropical regions (207 t/ha). Agroforestry aids climate change mitigation through carbon sequestration, as trees capture and store CO_2, decreasing atmospheric GHGs and mitigating climate change impacts on soil quality (Singh *et al.*, 2024).

The goods and benefits delivered by agroforestry systems are all included under the four categories of ecosystem service: provisioning, supporting, regulating and cultural. In terms of provisioning ecosystem services, the most common are food for humans (Kingazi *et al.*, 2024), medicinal and aromatic plants (Katsoulis *et al.*, 2022), feed for livestock (Salem *et al.*, 2020), wood for cooking, heating and construction purposes (Minini *et al.*, 2024), and feedstock for the bioenergy sector (Hassan, Williams and Jaiswal, 2019). These goods can be obtained from both trees and other cultured plant life forms. Furthermore, other by-products, such as spontaneously grown, usable native plants (Parada and Salas, 2024) and edible mushrooms (Silva-Neto *et al.*, 2022), have also been widely harvested in agroforestry systems. Where supporting ecosystem services are concerned, agroforestry systems are known for their high potential to increase soil quality and fertility (Fahad *et al.*, 2022), improve ecosystem biodiversity and health (Zhu *et al.*, 2024), and strengthen pollinator communities (Kingazi *et al.*, 2024). In terms of regulating ecosystem services, agroforestry systems are considered an effective means of mitigating the surface processes of (alluvial and fluvial) water overland flow and (water- and wind-derived) soil erosion (Mishra *et al.*, 2022), as well as carbon sequestration in the soil profile and plant tissue (Siqueira *et al.*, 2020). In terms of cultural ecosystem services, agroforestry systems constitute valuable cultural landscapes, contributing to rural quality of life (Plieninger *et al.*, 2020), preserving traditions and spiritual values, strengthening communities' sense of place (Mulyoutami *et al.*, 2023), and fulfilling additional aspects of human well-being (Ghale *et al.*, 2022).

Despite the thorough research on agroforestry, particularly on the challenges and opportunities involved with their functioning, many knowledge gaps still exist with regard to a wide range of aspects of these systems. Notably, a substantial research gap exists with regard to the impact of climate change on agroforestry functions and services. The forecast increase in the frequency and severity of droughts, on the one hand (Bjarke *et al.*, 2024), and the growing intensity of extreme precipitation events, on the other(Myhre *et al.*, 2019), may pose substantial challenges to agroforestry systems, particularly across the world's drylands (Koutroulis, 2019). Beyond the direct effect on soil water availability for trees and other plant life forms, such climatic trends may exacerbate processes of nutrient leaching and soil erosion, with a reduction in the overall functioning of agroforestry systems and the exacerbation of land degradation. Future efforts in agroforestry research should be focused on studying the specific mechanisms involved in such scenarios, as well as management practices that could potentially alleviate the adverse effects of such stressors.

Furthermore, despite the increase in knowledge and understanding of the benefits of agroforestry systems, there are substantial challenges preventing their widespread implementation. These include: the limited adoption of recommended management practices by resource-poor farmers; an emphasis on monocultural practices; low appreciation of indigenous species; inadequate coordination among various actors and stakeholders that promote agroforestry; the insufficient capacity of advisory services; a lack of joint platforms for sharing agroforestry-related information; weak institutional frameworks for the enforcement of environmental laws and regulations; a lack of specific policies and strategies for agroforestry development; complex bureaucratic processes and procedures in accessing donor funding; and global crises, such as conflicts and pandemics, which shift international funding priorities (World Agroforestry, 2021). Therefore, stakeholders, administrations, organizations and policymakers at the local, national, regional and international levels should work to remove such obstacles, to maximize the worldwide adoption of agroforestry systems, particularly across the planet's drylands.

On well-managed farms, the quantity, quality, diversity, accessibility and stability of food crop yields in agroforestry systems are expected to foster food security directly at household level (Duffy *et al.*, 2021). Similarly, feed produced in silvopastoral and agrosilvipastoral systems could further sustain a household's livestock, further strengthening the food security of its members (Salem *et al.*, 2020). The sale of excess food and feed crops, livestock products and wood material (Hughes *et al.*, 2020), as well as carbon revenues, could provide substantial income, strengthening household economic security (Waldén *et al.*, 2024). Furthermore, household economic revenues could increase substantially if they were to grow and sell high-value crops. For example, in agroforestry systems across the tropics, the cultivation of coffee and cocoa trees has often taken place under shade trees, such as Cordia alliodora (Somarriba *et al.*, 2024). A recent economic modelling study in sub-Saharan Africa showed that even when excluding carbon revenues, agroforestry systems are four times more profitable than major monoculture systems, particularly wheat, barley, maize, teff, sorghum, sugarcane and lentil, due to the sale of excess fruits (Waldén *et al.*, 2020). In addition, with the modelled carbon sequestration capacity ranging from 0.6 to 17.2 tC/ha/yr and carbon prices ranging from 8 to 40 USD/tCO_2e, the average carbon-related profitability of agroforestry systems was 150 percent above monocultural systems (Waldén, Ollikainen and Kahiluoto, 2020). Moreover, the environmental benefits of agroforestry systems – such as a reduction in on-site and off-site source pollution, a decrease in soil erosion (Fahad *et al.*, 2022), and an increase in carbon sequestration – are expected to improve environmental security (Waldén *et al.*, 2024). Another recent study highlighted the potential impact of agroforestry systems on reducing the occurrence of several concerns related to human health, thus increasing health security (Rosenstock *et al.*, 2019).

Many agroforestry systems have proven to be carbon-negative, that is, with carbon sequestration exceeding their GHG emissions. For example, a global meta-analysis of SOC pools revealed an average 25 percent or so decrease at a 0–30 cm depth upon land-use change from forest to agroforestry (De Stefano and Jacobson, 2018). At the same time, land-use change from agriculture to agroforestry increased SOC pools by an average of 26–40 percent at this depth and by an average of 34 percent at 0–100 cm depth. The conversion of grasslands to agroforestry increased SOC pools by an average of 10 percent at the 0–30 cm depth (De Stefano and Jacobson, 2018). This fits with a recent modelling study, which predicted greater SOC decomposition rates in grass monoculture systems than in silvopasture for RCP 8.5 (2060–2100), (Giannitsopoulos *et al.*, 2024).

BOX 5.1. Soil carbon sequestration in agroforestry systems - a meta-analysis

The data in the study by De Stefano and Jacobsen (2018) comprised a total of 250 observations from 52 publications covering more than 20 countries, mostly located in northern, central and southern America, Africa and Asia. To be included, studies had to contain information about soil carbon concentration on stocks per unit land sea (in Mg/ha/yr or other units). Three main agroforestry groups (treatment) were considered: i) agrosiviculture (crops plus trees), ii) silvopastoral (pasture/animals plus trees) and iii) agrosivilpastoral (crops plus pasture/animals plus trees). Non-agroforestry land uses (control) were grouped into five categories, according to the information provided by the authors: i) agriculture, ii) forest, iii) forest plantation, iv) pasture/grassland and v) uncultivated land/other.

In a recent study in Mozambique, SOC stocks were found to range from 25.6 and 33.7 tC/ha in grassland. Eight years after conversion to agroforestry, the SOC stocks were 61.1 tC/ha (with a mean SOC accumulation of 6.65 tC/ha/yr) (Magalhães, Reckziega and Paulino, 2025).

Another global meta-analysis showed that agroforestry systems had, on average, 46.1 tC/ha greater pools of biomass carbon than those in conventional croplands and pasturelands. In addition, systems with multiple tree species had greater biomass carbon pools and accumulated biomass carbon faster than systems with a single tree species. Also, soil carbon pools increased with tree age. However, systems in tropical regions reached peak level of soil carbon at a faster rate than those in temperate regions. At the same time, the latter peaked at a greater overall soil carbon level (Ma *et al.*, 2020).

Some agricultural soils have lost as much as 66 percent of their natural SOC pool (Don *et al.*, 2024). One of the most vital means of reducing CO_2 levels in the air is through soil carbon sequestration, which typically stocks carbon in the soil (Don *et al.*, 2024). Carbon sequestration can be supported by both natural and anthropogenic processes; the latter attempts to keep the world's carbon budget under control, so that there will be zero net releases of carbon in future (Saarikoski, Hutttunen and Mela, 2023). Remarkable strides can be made on reducing the impact of climate change by implementing IAS, including climate-smart agriculture (CSA) and/or conservation agricultural practices (Francaviglia, Almagro and Vicente-Vicente, 2023). These strategies decrease the generation and release of GHGs by promoting a rise in sustainable farming systems that can defy the threats of climate change (Nwaogu and Cherubin, 2024). A conducive climate, better soil quality, greater productivity, microbial activity and biodiversity are among the numerous benefits of SOC sequestration (Singh *et al.*, 2024; You *et al.*, 2024). By offsetting about 10 percent of annual GHG emissions, SOC sequestration could store a substantial quantity of carbon for a long time (Paul *et al.*, 2023). IAS is an all-round important farming system that has many definitions and benefits, as it can be practised in any climatic region and by farmers on any economic and land scale (Nwaogu and Cherubin, 2024). It is as highly profitable for large-scale, rich farmers, as it is for smallholder farmers in low-input and/or high-risk environments. Regardless of the farmer's financial status, the intercropping of cereals and legumes, crops and livestock, or the cultivation of crops or animals with trees can be practised. When correctly implemented, IAS can capture 0.9 GtC/yr in the soil, which is enough to offset 25-30 percent of the projected 3.3 GtC per year rise in atmospheric CO_2 (Subramanian *et al.*, 2023). In IAS, SOC sequestration has the capability to stock 30-60 GtC for 25—50 years or longer (Rodrigues, Brito and Nunes, 2023).

5.2. ADVANCES IN SUSTAINABLE AGRICULTURAL PRACTICES AND CARBON SEQUESTRATION

Advances in sustainable agricultural practices, including technological and technical approaches, are elements contributing to the vital paradigm shift from conventional agricultural systems to IAS, with a view to ameliorating climate change and its related impacts. While potentially sustainable and integrated agricultural approaches are implemented to increase SOC stocks and reduce their loss, advanced tools and techniques are recommended to support these goals and ensure accurate estimations. For example, in Canada, Khan *et al.* (2019) demonstrated that IAS, which involves precision agriculture consisting of site-specific nutrient management and variable rate irrigation, promoted crop yields and WUE, favouring climate change resilience.

BOX 5.2. Potential prospects of integrated agricultural systems (IAS)

- IAS is an important, all-round farming system, as it can be practised in any climatic region and by farmers on any economic or land scale (Nwaogu and Cherubin, 2024).
- It is a system that has become a promising alternative for sustainable agriculture, with productive plant—animal relationships, enabling environmental feasibility and economic dividends (Assmann *et al.*, 2014).
- IAS is a win–win, practically oriented agricultural system that incorporates socioecological systems with scientific, biotechnical, and social factors and processes, which are dedicated to the sustainable productivity of agricultural products in line with economic, environmental and societal well-being (Renting *et al.*, 2009).
- IAS can be defined as an agricultural system that combines the three possible components of agriculture — crops, livestock and forests — by applying these components to render mutual services to one another for profitable production (IFAD, 2010).
- IAS can also be described as the purposeful act of growing trees, crops and/or animals in relational integrations for several benefits and services, including the enhancement of crop production, contribution to food security, promotion of environmental services, resilience of agroecosystems, and mitigation and adaptability to climate change (Nwaogu and Cherubin, 2024).
- It is a sustainable and holistic approach to agriculture that involves the integration of various crops, livestock and other agricultural activities to maximize resource utilization, minimize environmental impact, and increase productivity and profitability (Agristudoc, 2023).
- IAS is a farming system that incorporates crop and livestock farming in a temporal and/or spatial framework (Lemaire *et al.*, 2014).
- It is a system that strives for synergies among the agroecosystem components for farm sustainability, while providing ecosystem and environmental services, and valuation of natural capital (Ponnusamy and Devi, 2017).

Similarly, Chao *et al.* (2019) established the efficiency of geospatial technologies in quantifying biomass productivity and detecting stress drivers in crops, prompting timely precautions to increase productivity and SOC content. Other technologies, such as soil health cards and Solvita soil health tests, need to be integrated into sustainable agriculture to empower farmers to make accurate and timely measurements of SOC (Guo, 2021). Combining local knowledge and scientific data, soil health cards, Solvita soil health tests and other advanced technologies can support farmers in monitoring changes in soil health over time, thereby ascertaining the impacts of their management practices on soil properties, including carbon.

TABLE 5.1. Socio-economic and environmental benefits of IAS from global perspectives

Sectoral dimensions	Benefits	Sources
Economic	Increases economic returns by providing minimal input usage	Farias *et al.* (2020)
	Provides income stability, that is, reduces economic risks through multiple production systems	Nwaogu and Cherubin (2024)
	Improves farmers' income by ensuring high production	Hui, Lu and Li (2022)
	Improves sources of income all round, as production is possible in all seasons	Farias *et al.* (2020)
	Increases income and production by suppressing weeds, pests and diseases	Grauby *et al.* (2022)
	Provides clean energy that reduces overdependence on fossil fuels	Thao *et al.* (2020)
Social	Improves human nutrition	Shanmugam *et al.* (2024)
	Creates job opportunities	Shanmugam *et al.* (2024); Sekaran *et al.* (2021b)
	Provides food security for better human health and well-being	Sekaran *et al.* (2021b)
Environment	Reduces inorganic fertilizer, pesticide and other inputs	Han *et al.* (2023)
	Increases carbon accumulation and biodiversity	Sekaran *et al.* (2021a)
	Enhances soil health through increased SOC storage, thereby improving agriculture sustainability and minimizing agriculture environmental impacts	Silva *et al.* (2024); Vanolli *et al.* (2025)
	Potentially reduces GHG emissions by improving environmental sustainability	Araujo *et al.* (2022)
	Promotes biodiversity and ecosystem services	Ca *et al.* (2022)

Contemporary technological advancements, including geospatial tools (such as geographic information systems [GIS] and remote sensing), big and robust data-driven tools (such as the CO_2fix, CENTURY, Roth C, PROCOMPAC, DNDC and SEN2COR models) and other technologies, have been efficiently applied to sustainable agricultural practices (Sharma *et al.*, 2023; Ramil Brick *et al.*, 2022; Banerjee and Palit 2024). The low costs of accessing these technologies and techniques can bring new awareness to agro-resource assessments for good management and policymaking. For example, Ramil Brick *et al.* (2022) reviewed a data-driven agroforestry tool that could be very effective when applied to agricultural systems. This technique enables farmers to exploit the relationships of a farming system to their advantage, while taking a sustainable agricultural approach that will benefit their crops, trees and livestock (Ramil Brick *et al.*, 2022). The SEN2COR tool (developed by the European Space Agency) has been widely employed for atmospheric correction in mapping the extent of farmland in the Colombian Andes (Bolívar-Santamaría and Reu, 2021) and Saskatchewan, Canada (Ha *et al.*, 2019). Geospatial technologies (remote sensing, such as unmanned aerial vehicles, satellite imagery and GIS) have been extensively used in the assessment and management of agroforestry (Sharma *et al.*, 2023). These can be extended to mapping and modelling SOC stocks in the fields.

The conversion of degraded or marginal lands into farmland has made sustainable agricultural practices an essential system for carbon sequestration. For example, studies have revealed that about 36 percent of the global agricultural land (2.7 billion ha) is marginal (Csikós and Tóth, 2023). While 11 percent and 27 percent of marginal lands are reported in South Asia and sub-Saharan Africa, respectively, other countries, such as Brazil and Russia, have more than 30 percent degraded or marginal lands (Csikós and Tóth, 2023; Bolfe *et al.*, 2024). Converting these degraded land areas to IAS could help achieve climate change resilience and food security by enhancing soil carbon stocks and soil health.

In Brazil, for example, recent studies report that degraded and marginal lands have been put into use to tackle a shortage of land, addressing a challenge faced by smallholder farmers in the region (Bolfe *et al.*, 2024; Freitas *et al.*, 2024). As a country with a large landmass, Brazil has used some of its degraded pasturelands for sustainable agriculture, yet vast areas of land are still degraded and not being used. According to Bolfe *et al.* (2024), Brazilian pastureland covers about 177 Mha, with 41 percent partially degraded and 21 percent severely degraded. The study recommends that as recovering degraded pastures is costly and time consuming, these lands should be converted to sustainable farming to increase carbon stocks, food and biodiversity. Another study on the Brazilian cerrado, meanwhile, reported that the transition from low-productivity pasture to sustainable farming generated a SOC and total nitrogen accretion of 5.22 t/ha/yr and 0.23 t/ha/yr, respectively, in the 0–40 cm soil layer (Freitas *et al.*, 2024). Land restoration activities were initiated in Ethiopia through the Productive Safety Net Programme, where rural communities and local governments contributed to an implementation process that restored about 7 500 ha of degraded land (Child *et al.*, 2021). In Mali, under the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) programme, large areas of marginal land were restored for agriculture (Africa, Southern., 2016). In Ethiopia and Mali, the restoration of the degraded lands supported an increase in SOC stocks and productivity (Birhanu *et al.*, 2024), with more than 200 agropastoral households and millions of living fauna and flora species benefiting from such projects.

However, in Africa, these restoration initiatives are very limited. Inadequate lands are becoming a serious threat to farmers, as most have been degraded due to rapidly growing populations, intensive tillage, and slash-and-burn cultivation. Poor resources and climate extremes have exacerbated the situation (Zerssa *et al.*, 2021). Some studies have called for the transformation of the degraded lands to agricultural food production through sustainable agricultural practices characterized by high SOC sequestration and food security (Zerssa *et al.*, 2021; Child *et al.*, 2021).

Meanwhile, the inability to restore or convert degraded or marginal lands into sustainable agriculture tends to be common in most developing countries in Africa, Asia and Latin America, due to a lack of technology, techniques and finance. Even though many sustainable agricultural practices are relatively low cost, they may not be affordable for poor farmers suffering from low income, limited land and low productivity. Consequently, interventions by developed economies and international organizations are needed to assist these low-economic countries in increasing SOC sequestration by transforming their degraded lands. Interventions should not stop at procuring technology or releasing capital. They should also ensure that technologies and funds reach rural farmers, are not hijacked for other purposes and are properly managed to achieve the targeted goals. In addition to promoting climate change mitigation, such measures will help to increase food security and achieve other SDGs, such as SDG 1 (No Poverty) and SDG 15 (Life on Land).

5.3. PERENNIAL CROPS, INCLUDING BIOMASS FOR ENERGY

The recent introduction of bioeconomy strategies (for example, food waste recycling, biowaste treatments, phycoremediation, biomass gasification, nano-composition, vermiculture and vermicomposting) into agricultural systems has boosted the cultivation of bioenergy crops. These approaches are effective, sustainable alternatives for reducing GHG emissions and improving energy supply and food security globally. Yu *et al.* (2024) estimate that bioenergy crop cultivation could counteract almost 47.9 percent of all agricultural GHG emissions produced in China in 2020. The harnessing of biomass for energy produces a net-zero carbon footprint, as the CO_2 emitted during biomass combustion is offset by the CO_2 absorbed during biomass growth (Alper *et al.*, 2021). Energy crops and biomass are vital contributors, as they effectively diminish GHG emissions (Forsberg *et al.*, 2021). Perennial bioenergy plants, such as sugar cane, agave, palm oil, jatropha, date palm, Eucalyptus spp, napier grass, switchgrass, alfalfa, sunflower, timothy grass and reed canary grass, have been successfully used as high-energy-producing sources to support transportation, industrial and domestic energy needs and diminish GHG emissions. In addition, energy from biomass has also gained global popularity as a vital material in the fight against the changing climate.

Biomass is organic material derived from plants, animals or microorganisms that can be living or dead and waste. The advent of biomass as a vital energy source has reduced pressure to use food crops for bioenergy, as waste from crops such as sugar cane, palm oil, soybeans, wheat and corn is now being used to produce bioenergy. This has significantly decreased pollution from agricultural waste, reducing emissions from agricultural systems. The (perennial/annual) biomass from different plant species has been exceptionally beneficial in mitigating climate change. For instance, in Europe, biomass from perennial grass species is becoming well known, particularly miscanthus (Miscanthus sp.), because of its high productivity. Studies have also shown that miscanthus possesses greater potential for mitigating CO_2 emissions than maize (Rostocki *et al.*, 2024).

5.4. SILVOPASTURE INCLUDING ASSISTED NATURAL REGENERATION AND FARMER-MANAGED NATURAL REGENERATION

The contributions of silvopasture in mitigating climate change have been widely studied. Silvopastoral systems refer to planned combinations of trees, forage herbs and livestock, and constitute about 28 percent (450 Mha) of the global area of agroforestry systems. Because of their broad distribution, their capacity to increase SOC and, therefore, contribute to carbon sequestration, enhance soil quality, improve ecosystem services, such as water and nutrient cycling, and boost livestock well-being (Ortiz *et al.*, 2023), is relevant at a global level, even if their contributions vary in different places, depending on numerous factors and baseline conditions.

Silvopastoral systems have been proposed to manage and restore drylands (FAO, 2022). Direct carbon inputs to the soil occur in the form of litterfall from the trees, organic matter from grazing livestock and the below-ground residue of woody species in both topsoil and subsoil (Ortiz *et al.*, 2023). In a recent review, Ortiz *et al.* (2023) observed that 1–5 tC/ha/yr were captured in above-ground biomass, while SOC accumulation rates below ground were 1.8–7.5 tC/ha/yr. The conversion of grasslands to silvopastoral systems led to an estimated carbon accumulation of 4.4 tC/ha/yr.

In Ecuador, Iñamagua-Uyaguari, Fitton and Smith (2023) found that transforming riparian and steepland pastures into sillvopastoral systems could deliver important carbon sequestration benefits, with a reduction in pasture biomass production of less than 20 percent. In Argentina, the cattle-breeding systems of native forests in the Entre Ríos province reported average carbon storage values of 65 tC/ha in the soil (at 0—30 cm) and 20 tC/ ha in tree biomass, varying with forest type and grazing intensity (Peri *et al.*, 2024). In Chiapas, Mexico, the average SOC sequestration rate of silvopastoral systems was estimated at 0.143 ± 0.043 tC/ha/yr to a 50 cm depth (for silvopasture with tree plantations of different ages, between two and ten years). The SOC sequestration rates had a positive correlation with silvopasture age at the beginning, decreasing after about eight years (López-Hernández *et al.*, 2024).

Macedo *et al.* (2024) found SOC carbon in different aggregate sizes to have increased significantly (38 percent) in silvopasture compared with forest and pastures. Conversion of forest to pasture significantly reduced aggregate stability and carbon sequestration in all aggregate sizes, but the implementation of silvopasture increased food production and carbon stocks. Similarly, a recent study in the Colombian Amazon found SOC stocks under silvopasture and alley cropping to have increased compared with pasture, native and secondary forests (Suárez, Segura and Andrade, 2024). Latin America has the largest areas of agroforestry (including silvopasture) globally. A study covering Argentina, Brazil, Colombia, Mexico and Uruguay focused on the environmental impacts of agroforestry (López-Sampson and Andrade, 2024). Mean annual carbon sequestration rates ranged from 0.25 tC/ha/yr to 2.57 tC/ha/yr in biomass and 0.14 tC/ha/yr in soils under silvopasture, substantially higher than in agricultural areas (López-Hernández *et al.*, 2023).

Integrating these technologies with farmer-managed natural regeneration, an agroforestry systems programme operating in the arid and semi-arid regions of Africa and Asia, can be very successful (Dagar, Gupta and Dimobe, 2024). The positive results of maximum adoption of agrosilvipasture and the integration of these technologies into the system in Latin America prompted Adegbeye, Ospina and Waliszewski (2024) to recommend applying such techniques in Nigeria and other African countries.

5.5. INTEGRATED AGRICULTURE—LIVESTOCK SYSTEMS

Integrating agriculture with livestock has numerous socioeconomic and environmental benefits especially carbon sequestration and emission reductions. Integrated agriculture—livestock (IAL) systems cover many practices that can be referred to as CSA, low-carbon agriculture, agrosilvipastoralism and other practices. In Mexico, IAL and forest remnants (27–163 percent) have been identified as having stored much more carbon than open pasturelands (Khan *et al.*, 2024; Aryal *et al.*, 2022). In Nicaragua, increased tree coverage was reported in degraded pastures transformed into IAL systems, enabling carbon sequestration to be promoted in degraded lands through agroforestry (Cárdenas *et al.*, 2019). In Ecuador, the Union of Cacao Peasant Organizations established a cacao agroforestry initiative that was found to have sequestered 55.1 tC/ha, 7 percent higher than the value obtained in an adjoining non-agroforestry area (Allen *et al.*, 2024). In the Ñuble region of Chile, three degraded sites with previously open, semi-open and semi-closed canopies were transformed into a silvopasture. SOC stocks were found to have increased in the previously open (22.5 t/ha), semi-open (14.5 t/ha) and semi-closed (4.8 t/ha) canopy, indicating that agroforestry assisted the restoration of soils in the region (Ortiz *et al.*, 2020).

In Africa, Tschora and Cherubini (2020) reported that a large-scale application of IAL in seven West African countries could stock up to 135 $MtCO_2$/yr in two decades, equivalent to 166 percent of carbon emissions from fossil fuels and deforestation in the region. In cacao agroforestry over a 20-year period in Côte d'Ivoire, it was established that the total carbon stock per ha rose by 71 percent by intercropping cacao with Acacia mangium (Silue *et al.*, 2024). Similarly, in Cameroon, the afforestation of gramineous-woody savannah with cocoa agroforestry systems showed a remarkable increase (17.8 gC/kg) compared with the adjacent savannah or cocoa monoculture (3.4 gC/kg) (Fonkeng *et al.*, 2024). This was down to the higher annual litter input accrued in the cocoa agroforestry systems.

In line with the NDC of India, Nath *et al.* (2021) quantified the carbon stocks and sequestration prospects of agroforestry systems under distinct management. The study projected that by 2050, under IAL (such as agrisilvicultural, agrosilvipastoral and silvopastoral) systems, the total amount of carbon sequestered would be 4.2 $GtCO_2e$, 4.5 $GtCO_2e$ and 1.5 $GtCO_2e$, respectively, and the sequestered carbon would increase with an increase in the agroforestry area(s). In the Corn Belt of the United States, IAL (such as agroforestry) was found to have increased SOC content and food production compared with adjacent annual cropland (Kasmerchak *et al.*, 2024). Without compromising economic returns, implementing IAL in the Corn Belt elevated faunal biodiversity across trophic levels and improved SOC and soil health (Kasmerchak *et al.*, 2024).

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6. Livestock

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6.1. RECENT ADVANCES IN METHODOLOGICAL APPROACHES TO GLOBAL ASSESSMENTS OF GREENHOUSE GAS EMISSIONS FROM LIVESTOCK IN FOOD SYSTEMS

Several global syntheses of GHG emissions from the livestock sector have been published since 2018, including the latest FAO global assessment of GHG emissions and mitigation options (FAO, 2023). Using a life-cycle assessment (LCA) approach, the report estimates emissions from the global livestock sector at 6.2 $GtCO_2e$/yr, equal to around 12 percent of all anthropogenic GHG emissions and about 40 percent of total emissions from agrifood systems. Without intervention and productivity gains, meeting increased demand is likely to bring global livestock emissions to nearly 9.1 $GtCO_2e$ by 2050. However, by applying all currently available mitigation strategies from both the demand and supply sides, the report estimates that global livestock emissions could be brought down to 1.9 $GtCO_2e$ by 2050, with the majority of this reduction potential coming from supply-side measures.

The Global Methane Pledge of 2021, launched at COP 26 in Glasgow, has also triggered increased interest in reporting livestock CH_4 emissions and assessing their mitigation potential separately. This has led, in particular, to raised awareness of the inadequacy of available data and CH_4 emission factors for extensive or smallholder livestock systems in low- and middle-income countries (LMICs), as well as the implications of the GWP metric used for CH_4. Both factors have a significant impact on global assessments of food systems and their environmental impact (Scoones, 2022). On the first point, respective evidence from Assouma *et al.* (2019) and Ndung'u *et al.* (2018) reveals that Tier 1 enteric CH_4 emission factors can overestimate emissions by up to 76 percent for cattle during the dry season in Senegal and up to 8 percent for dairy heifers in Western Kenya. On the latter point, applying GWP, Costa *et al.* (2021) showed that a sustained annual decline of around 0.35 percent in agricultural CH_4 emissions would be sufficient to stop further increases in global temperatures from agricultural CH_4 emissions. Conversely, a 1.5 percent annual increase in agricultural CH_4 emissions would lead to climate impacts about 40 percent greater than those suggested by GWP over 100 years (GWP100).

Another area of progress is nutrition. Global food security has deteriorated over the past decade, while nutrient deficiency has increased. According to Passarelli *et al.* (2024), more than half of the world population lacks essential nutrients such as iron, folate and calcium. Recent reviews have focused on integrating environmental and nutritional outcomes of dietary choices (Beal *et al.*, 2023).

Studies using LCAs to identify sustainable agrifood systems that address malnutrition are starting to consider the quality of proteins, using amino acid scores (McAuliffe *et al.*, 2023; FAO 2023) and the concentration of micronutrients of different foods (Katz-Rosene *et al.*, 2023). This approach seeks to overcome the limitations of previous analyses that primarily relied on kilocalorie or protein content alone (Beal, 2024; Beal, Ortenzi and Fanzo, 2023). By considering these additional nutritional quality metrics, LCAs provide a more comprehensive evaluation of food systems, promoting sustainable diets that not only meet energy needs, but also support optimal health outcomes.

Such considerations have led to reports such as the Bill and Melinda Gates Foundation (2024) Goalkeepers Report, which estimates that improving dairy productivity and supply in five countries — Ethiopia, India, Kenya, Nigeria and the United Republic of Tanzania — could prevent 109 million cases of childhood stunting between 2020 and 2050.

In addition, land-use efficiency is a concept that has made progress in assessing the sustainability of current food systems. This approach takes into account the edibility of livestock feed for humans and the potential to convert pastures and rangelands into croplands, and demonstrates that in certain agrifood systems, grazing livestock can be the most sustainable option (Hennessy *et al.*, 2021; Battheu-Noirfalise *et al.*, 2023).

Despite these advancements, global assessments of food systems and their environmental impact that include these recent methodological developments remain rare. For example, they are not included in the latest LCA global assessment by FAO (2023).

6.2. FEED AMENDMENTS AND ADDITIVES

In the last two decades, interest in reducing emissions from livestock has increased. Optimized feeding strategies, including balancing feed rations and incorporating feed additives or nutritional supplements, are some of the most promising approaches to mitigating CH_4 emissions in livestock (Fischer, Edouard and Faverdin, 2020). According to a meta-analysis by Arndt *et al.* (2022), different dietary mitigation strategies are effective at decreasing emission intensities (emissions per unit of milk and gain), including increasing feeding level, decreasing grass maturity and decreasing dietary forage-to-concentrate ratio, although they do not decrease absolute CH_4 emissions. In addition, there are strategies that are effective in both decreasing emission intensities and absolute CH_4 emissions: CH_4 inhibitors, tanniferous forages, electron sinks and lipids. Supplementation with lipids, for example, from processed oil seed and oils, can be used to reduce CH_4 emissions by changing the products of fermentation and/or through the inhibitory effect on methanogens. Beauchemin *et al.* (2022) and Roques *et al.* (2024) conclude that strategies targeting methanogens can be highly effective, achieving reductions in enteric

CH_4 emissions of up to 80 percent. In contrast, Hegarty *et al.* (2021) reviewed 10 additive groups and found that only two — 3-nitrooxypropanol and dried Asparagopsis (red algae) — consistently delivered reductions of more than 20 percent, while dietary nitrate, the third-most effective additive, safely achieved mitigation of 10 percent or more when included in the diet. However, the applicability of these mitigation strategies to different production systems and their relevance in a number of contexts is variable, with less feasibility in grazing systems and LMICs. Therefore, more tailored research is needed to identify anti-methanogenic measures relevant to grazing systems, which represent 29 percent to 45 percent of ruminant systems.

Promisingly, some recent research has focused on grazing systems. For example, a recent review by Vargas *et al.* (2022) explored strategies for modifying feed in grazing systems to reduce CH_4 emissions, highlighting legume fodder and bush as the most promising options. Similarly, Abraham, Kechero and Andualem (2023) examined the potential of indigenous legume fodder trees and shrubs in Ethiopia as CH_4-reducing amendments and found substantial variation in CH_4 production between species.

BOX 6.1. New developments: hydroponic fodder production for reduced land competition and mitigation

Feed amendments should be considered in terms of overall GHG emissions, including those associated with their production. This has generated interest in using techniques such as hydroponics to reduce emissions associated with feed production, but also land use and land-use change, although the scale at which this would be feasible and the circumstances in which it could be applied need careful assessment. Newell *et al.* (2021) compared GHG emissions from hydroponically and conventionally grown barley fodder in Canada. The results indicated that hydroponic systems have the potential to reduce emissions when energy consumption is taken into account and assumed to be from renewable sources. Small-scale hydroponic fodder production is developing in various regions, including, for example, in Rwanda and India (Harerimana *et al.*, 2023; Rugwiro, 2024; Shit, 2019).

6.3. GENETIC SELECTION

Selection for reduced CH_4 emissions is a growing area of research (Lassen and Difford, 2020; De Hass *et al.*, 2021). Recent studies have shown a permanent and cumulative effect over generations resulting from selection for low CH_4 emissions (Rowe *et al.*, 2019). However, a significant limitation is the lack of economic incentives for farmers to select animals based on these criteria. Genomics has so far been mostly conducted in dairy systems in high-income countries, and there are more challenges in LMICs (Ducrocq *et al.*, 2018).

Measuring CH_4 emissions directly is costly and technically challenging, prompting most researchers to rely on production performance variables as proxies to estimate CH_4 yield. Research has also shown that the level of CH_4 emissions from a selected breed is a response to the combination of the host genome and the microbiome genome (Hess *et al.*, 2023). Despite these findings, Roques *et al.* (2024) conclude in their review that the genetic basis of CH_4 emissions in ruminants is still not understood fully, and further research is needed, particularly on the use of proxies to predict CH_4 emissions and on host-microbiome interactions.

6.4. MANURE MANAGEMENT

6.4.1 INCREASE IN FREQUENCY OF MANURE REMOVAL REDUCES IN-HOUSE GHG EMISSIONS

Zhang *et al.* (2024) found that the daily removal of manure from pig houses with a scraper reduced CH_4, CO_2 and N_2O emissions by 71 percent, 67 percent and 6 percent, respectively, compared with the removal of manure every 44 days (pull-plug system), as it decreased manure fermentation in animal houses. However, while the more frequent removal of manure for storage outside housing facilities can lower gaseous emissions from on-site storage, the longer storage time outside may increase emissions. Ma *et al.* (2023), meanwhile, found that the removal of slurry from indoor storage once or three times per week, compared with removal once after 40 days, reduced total CH_4 emissions from manure by 18–41 percent in summer and 53–83 percent in winter. One possible explanation is that the shorter time that slurry resides in pig houses delays the development of active methanogenic populations, while outdoor storage usually has a lower temperature, so microbial activity is lower, contributing to the reduction in CH_4 emissions (Dalby *et al.*, 2023).

6.4.2 DIETARY MANIPULATION STRATEGIES TO REDUCE NITROGEN EXCRETION

Reducing crude protein content in the diet of livestock can lower nitrogen excretion. This can be achieved by better aligning the quality of protein fed and required by the animal, improving nitrogen efficiency. A meta-analysis conducted by Wang *et al.* (2020) showed that lowering crude protein content significantly reduced total nitrogen excretion (by 28.5 percent). Similarly, Cappelaere *et al.* (2021) found a reduction in nitrogen excretion of 7.5—10 percent for each 10 g/kg of crude protein reduction in pig production, potentially reducing resultant N_2O emissions. To avoid any loss of productivity by reducing dietary crude protein, supplementation with synthetic amino acids is being used extensively. Xu *et al.* (2022) estimated that the low crude protein used in the livestock sector in China could help to reduce livestock N_2O emissions by 8 percent. Other dietary manipulations that can reduce nitrogen excretion from pig manure involve the addition of protease and other additives (such as fermentable carbohydrates, acidifying agent/salts and probiotics) (Wang *et al.*, 2020).

6.4.3 ACIDIFICATION FOR CONTROLLING GHG EMISSION FROM SLURRY STORAGE

Shin *et al.* (2019) found that slurry acidification by sulphuric acid (H_2SO_4) to pH values of 7.0, 6.5, 6.0, 5.5 and 5.0 can help reduce CH_4 emissions by 51—93 percent over a 40-day pig-slurry storage period at less than 30 °C. The acidified pig slurry showed higher CH_4 yields in the subsequent anaerobic digestion stage than in the control stage, presumably as the degradable organic matter in the slurry was kept under acidic conditions. Ma *et al.* (2022) proved that the CH_4 mitigation effect could reach 46—96 percent when different levels of H_2SO_4 are added in a pilot-scale storage facility and that the mitigation was achieved at a cost of EUR 28—134 (~USD 30—150) per tCO_2e. The study found that alkalinization can also reduce GHG emissions by having an effect at the microbial level. The pH ranges for maximum CH_4 and N_2O emissions were 7.5–8.5 and 6.5–8.5, respectively, and slurry with a pH of 7.5–8.5 showed the highest GHG emissions. Acidification to a pH of 5.5 helped reduce CH_4, N_2O and total GHG emissions by 98.0 percent, 29.3 percent and 81.7 percent, respectively, while alkalinization to a pH of 10.0 helped achieve mitigation effects of 74.1 percent, 24.9 percent and 30.6 percent, respectively (Wang *et al.*, 2023). The inhibition of functional genes, such as methyl-coenzyme M reductase mcrA, ammonia monooxygenase amoA, nitrate reductase narG and nitrite reductase nirS , by an unsuitable pH was key to the low emissions. In addition, the combination of H_2SO_4 acidification and temperature decrease was found to reduce CH_4 emissions by 69 percent and be effective in the eco-friendly storage of pig slurry (Im *et al.*, 2020).

6.4.4 BIO-ACIDIFICATION TECHNOLOGY FOR SLURRY HAS GAINED MORE ATTENTION

In addition to chemical acidification, a new bio-acidification technology that induces the self-production of lactic acid in stored slurry with the addition of carbon-rich organic matter was found to be a promising method of reducing GHG emissions from slurry storage (Kavanagh *et al.*, 2021; Prado *et al.*, 2020; Bastami, Jones and Chadwick, 2021). Cong *et al.* (2023) found that the lactic acid concentration could reach 10 000–52 000 mg/L chemical oxygen demand by adding apple waste to pig slurry with some inoculum, while the pH remained within 4.5, and the CH_4, N_2O and GHG emissions decreased by 87 percent, 57 percent and 86 percent, respectively, compared with control. The significantly reduced copy numbers of mcrA and nitrogen transformation functional genes (amoA and nirS) in the bio-acidified slurry contributed to the reduction in CH_4 and N_2O emissions. Prado *et al.* (2020) found that adding sugar or whey to cow manure for storage could achieve 97 percent and 34 percent N_2O emissions reductions, respectively. However, N_2O emissions increased with a rise in pH and surface crust (Prado *et al.*, 2020). Gioelli *et al.* (2022) did not find a significant N_2O mitigation effect, as crust formation may provide good conditions for N_2O emission. Agricultural waste that could potentially be used in the bio-acidification technology includes sugarbeet molasses, grass silage and brewer's grain (Kavanagh *et al.*, 2021).

6.4.5 ADDITIVES USED FOR MANURE GREENHOUSE GAS MITIGATION

Pereira *et al.* (2022) found that biochar additives can help reduce CH_4 and N_2O emissions from slurry by 67 percent and 24 percent, respectively. Biochar was also found to achieve synergistic mitigation effects for both CH_4 and N_2O emission from manure compost systems, with N_2O being reduced by 15–80 percent and CH_4 being reduced by 60 percent (Liu *et al.*, 2023; Guo *et al.*, 2020). However, Liu *et al.* (2021) found that adding coconut shell biochar may induce an increase of 600–700 percent in CH_4 emissions from slurry storage. Chiodini *et al.* (2023) found that a commercial additive of 100 percent calcium sulphate dihydrate (gypsum) at a dose of 2g/week for dairy cattle in commercial animal farms can help reduce CH_4 emissions from slurry by up to 80 percent. Peterson *et al.* (2020) found that gypsum-based commercial additives can also help reduce N_2O emissions from slurry in laboratory tests. A calcium superphosphate additive helps reduce N_2O emissions by 79 percent and CH_4 emissions by 32 percent in manure compost systems (Zhang *et al.*, 2020). Nitrification inhibitors such as dicyandiamide were found to reduce N_2O emissions by 25–40 percent and CH_4 by 10–40 percent (Yang *et al.*, 2022). In addition to additives applied directly to manure, feed additives can also help modify manure characteristics and reduce gas emissions. Lee and Ahn (2023) found the CH_4 emissions from piggery slurry stored in slurry pits to be reduced by 44 percent by adding peat moss to the diet of pigs

6.4.6 BIOGAS RECOVERY IS PROMISING FOR MANURE GREENHOUSE GAS MITIGATION

Manure management with a biogasification plant can also decrease whole-farm emissions. Vechi, Jensen and Scheutz (2022) evaluated whole-farm-level CH_4 emissions using the tracer gas dispersion method and found that CH_4 emissions from pig farms with slurry being treated with biogas plants can be 55 percent lower than from farms with no manure treatment. A life-cycle assessment study at farm level, meanwhile, showed that anaerobic digestion technology may reduce GHG emissions from manure management systems by 58–80 percent depending on the region of the United States (Greene *et al.*, 2024).

6.4.7 COVERAGE FOR REDUCING GREENHOUSE GAS EMISSIONS FROM MANURE MANAGEMENT

Lagoon coverage plays an important role in reducing total GHG emissions. Wang *et al.* (2024) evaluated the CH_4 mitigation potential of the livestock sector in China and found that if all current lagoons were covered, national total CH_4 emissions from manure management could be reduced by 37 percent. Coverage is also effective in reducing GHG emissions from manure compost systems. Xu *et al.* (2024) found that CO_2, CH_4 and N_2O emissions were reduced by 82 percent, 87 percent and 83 percent, respectively, by using a membrane-cover composting system based on industrial-scale experiments. They also found that the microaerobic conditions formed in the membrane covering the compost pile, together with the cover-inhibiting effect, dominated the mitigation effect. The CO_2, CH_4 and N_2O concentrations detected outside the membrane were 64 percent, 70 percent and 55 percent lower, respectively, than those detected inside the membrane (Fang *et al.*, 2021).

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7. Oceans and coastal areas

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The livelihoods of around 600 million people depend wholly or partially on aquaculture and fishing (FAO, 2022). An understanding of the contribution that aquaculture and fisheries make to food security and nutrition is, therefore, essential. This is particularly true in the face of the current climate and biodiversity crisis, where aquaculture and fisheries have the potential to play an even bigger role in global food systems, prompting the United Nations to designate 2021–2030 as the Decade of Ocean Science and Sustainability.

Two sections of this report consider the topic. Section 7 explores new research on the status of and threats to oceans and coastal areas, while Section 8 considers aquatic food production.

7.1. MANGROVES

Mangroves cover 137 000 km^2 of the earth's surface (Bunting *et al.*, 2022). The historically rapid rates of ecosystem loss have slowed, although degradation continues in many countries (see, for example, Adame *et al.*, 2024). The conservation of mangroves prevents GHG emissions and maintains carbon sequestration and storage (Adame *et al.*, 2022). In addition to climate mitigation benefits, there are benefits in terms of adaptation to climate change and extreme climate events, for example, through reduced coastal flooding, which have been valued at more than USD 250 million per year (Menéndez *et al.*, 2020). Fisheries and biodiversity preservation are additional key benefits of conserving and restoring mangroves (Zu Ermgassen *et al.*, 2020; Sievers *et al.*, 2019).

Restoration of mangroves sequesters carbon in soils and biomass (Macreadie *et al.*, 2021; Su, Friess and Gasparatos, 2022), albeit to a lesser extent (about 75 percent) than natural mangroves (Bourgeois *et al.*, 2024). Additional GHG reduction benefits include reduced emissions from prior land uses (Lovelock *et al.*, 2023) and the export of alkalinity to coastal waters, increasing CO_2 fluxes to the oceans (Fakhraee, Planavsky and Reinhard, 2023).

Monitoring data on changes in the extent of mangroves are made available annually (Bunting *et al*,. 2022). Along with maps of soil carbon stocks in mangroves (Sanderman *et al.*, 2018), models of above-ground biomass have been refined (Simard *et al.*, 2019, updated in 2024), providing resources for estimating carbon stocks and changes in carbon stocks over time.

Cumulative and synergistic impacts of anthropogenic influences (such as coastal squeeze) and climate change impacts (such as sea-level rise, extreme climatic events and changes in precipitation and temperature) are expected to have negative impacts on mangroves (Friess *et al.*, 2022). Impacts of sea-level rise are projected to be more extreme on the American continent than in the Indo-Pacific region (Saintilan *et al.*, 2023) and result in losses of habitat in areas where there are high levels of coastal squeeze (Schuerch *et al.*, 2018). Accurate elevation data are limited globally, so assessments of climate risks for coastal wetlands are currently modelled on the scale of geomorphic units (Schuerch *et al.*, 2018) or locally, where data are available (Mazor *et al.*, 2021).

7.2. SEAGRASS

Global seagrass areas are the largest of all coastal wetlands (estimated at up to 600 000 km^2), but their extent is still uncertain, owing to the difficulty of mapping subtidal habitats. However, mapping is improving rapidly (McKenzie, Langlois and Roelfsema, 2022). Threats to seagrass are high, particularly from poor water quality and marine heat waves (Turschwell *et al.*, 2021). Data on sediment carbon stocks and sequestration rates have increased apace in recent decades (Krauss *et al.* 2025.). Although carbon stocks and sequestration rates are low (compared with other blue carbon ecosystems), the large extent of seagrass provides opportunities for mitigation with conservation and restoration (Macreadie *et al.*, 2022).

Conservation and restoration have benefits for coastal protection (Twomey *et al.*, 2022), biodiversity (Sievers *et al.*, 2019), carbon storage (Oreska *et al.*, 2020) and culture (Sinclair *et al.*, 2024), and are increasingly well characterized. Seagrass has been included in IPCC GHG Guidelines, but guidance is limited to estimating emissions from losses associated with excavation and the accumulation of SOC from restoration through rewetting (IPCC, 2013).

Climate risks are associated with marine heatwaves (Serrano *et al.*, 2021) and extreme storms (Correia and Smee, 2022). Sea-level rise may reduce the extent of deep-water seagrass (Saunders *et al.*, 2013), and losses could be greater where migration to shallower water is prevented by coastal development (Capistrant-Fossa and Dunton, 2024).

7.3. TIDAL MARSH

Tidal marshes cover at least 90 800 km^2 and their global magnitude is relatively stable (Murray *et al.*, 2022). Losses have occurred over centuries, and the conservation and restoration of tidal marshes are increasing with recognition of their important role in coastal protection and carbon sequestration (Waltham *et al.*, 2021).

Similar to mangroves, climate change threats are intensified by anthropogenic stressors, with coastal squeeze giving rise to projected losses in future (Schuerch *et al.*, 2018). Losses of tidal marsh to sea-level rise are occurring in many locations and are linked to high rates of relative sea-level rise and limited sediment supply, often due to the hydrological modification of waterways (Saintilan *et al.*, 2022). Restoration techniques for tidal marshes are already fairly advanced (Billah *et al.*, 2022).

7.4. SEAWEED

Seaweeds are highly productive and can be separated into natural ecosystems (blue forests or ocean forests, often referring to brown algae on rocky substrates) and those used for aquaculture. They are important for supporting biodiversity, fisheries and coastal protection, and provide a range of services to people (Cotas *et al.*, 2023; Eger *et al.*, 2023). Seaweed is widely used in food and industrial products and becoming more common place globally (Kilinç *et al.*, 2013; Cai *et al.*, 2021). Natural seaweed ecosystems are threatened by coastal development, poor water quality, overexploitation and climate change (Hamilton *et al.*, 2022).

Storage of carbon through the conservation and restoration of seaweed is linked to the export of particulate organic matter to deep waters of the oceans (Filbee-Dexter *et al.*, 2024). Storage of organic carbon in the sediment below seaweed farms has also been observed in some sites (Duarte, Bruhn and Krause-Jensen, 2022). Seaweeds are not yet included in IPCC guidelines, but will be considered in a new methodology report on CDR for 2027.

7.5. ACCOUNTING FOR ECOSYSTEM SERVICES IN COASTAL WETLANDS

Mangroves, tidal marshes and seagrass are included in the 2013 supplement to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2013) and have been incorporated into environmental economic accounting approaches (Costa *et al.*, 2024). Carbon accounting methods for the restoration of blue carbon ecosystems for carbon markets have been developed by VERRA, Gold Standard and Plan Vivo (Macreadie *et al.*, 2022), although uncertainties remain with regard to some pools and fluxes, and the implementation of projects can be challenging (Williamson and Gattuso 2022; Lovelock, Barbier and Duarte,2022). There are also national methods in a range of countries, including Australia, China, Japan, Mexico and Thailand (Kuwae *et al.*, 2022; Lovelock *et al.*, 2022; Adame *et al.*, 2024; Li *et al.*, 2024), and are under development in the United Kingdom of Great Britain and Northern Ireland. The IPCC will produce a new methodology report in 2027, which will update guidance on the restoration of coastal wetland ecosystems.

Interest in the restoration of coastal wetland ecosystems for mitigation and co-benefits (biodiversity, fisheries and adaptation to climate change) has led to advances in technologies for coastal wetland restoration in recent decades (Billah *et al.*, 2022; Beeston *et al.*, 2023; Unsworth *et al.*, 2024). There have also been more advances in remote sensing of coastal wetland ecosystems (Malerba *et al.*, 2023), increasing confidence in verification and reducing costs.

7.6. RESTORATION OF COASTAL WETLANDS ON FLOODED LANDS

Flooded lands are defined as water bodies where human activities have caused changes in the amount of surface area covered by water, typically through water level regulation (IPCC, 2019). This category of land includes drained landscapes, landscapes dominated by ponds (such as shrimp aquaculture), and agricultural land uses, such as wet pastures formed by building bund walls. Flooded lands emit CO_2, CH_4 and N_2O, so their restoration to coastal wetlands can reduce GHG emissions, as well as enhance carbon storage in biomass and soils and provide other ecosystem services (Adams *et al*., 2021; Kroeger *et al*., 2017; Tully *et al*., 2021). Restoration of flooded land has occurred where aquaculture productivity has declined (Aslan *et al*., 2021) and to enhance the resilience and sustainability of aquacultural landscapes (McSherry *et al*., 2023). Restoration of degraded aquaculture and agriculture to coastal wetlands can be economically feasible (Duncan *et al*., 2022; Friess *et al*., 2022), in addition to offering biodiversity benefits and other ecosystem services (Fu *et al*., 2024). The restoration of coastal wetlands on agriculture and aquaculture land uses occurs in response to the need to restore coastal protection, recovery fisheries, increase biodiversity and sequester carbon (Hagger, Waltham and Lovelock, 2022; Rogers *et al*., 2022). In many locations where mangroves have been removed for aquaculture (for example, in Southeast Asia), aquaculture ponds have been found to have low productivity due to declining water quality (Aslan *et al*., 2021). In such cases, restoration of coastal wetlands is undertaken (Cameron *et al*., 2019; Sidik, Adame and Lovelock, 2019) and can have a high return on investment (Duncan *et al*., 2022).

References - Section 7

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8. Aquatic food production

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8.1. MARINE CAPTURE MARINE FISHERIES

Aquatic animal foods account for at least 20 percent of the per capita animal-protein supply of 3.2 billion people, or more than 40 percent of the world's population (FAO, 2024a). With 80 Mt of aquatic animals produced in 2022, marine capture fisheries remain a significant global source (43 percent) of aquatic animal foods, with the rest coming from inland fisheries, particularly marine- and land-based aquaculture. The potential of aquatic foods to boost their contribution to food security, nutrition and poverty reduction is increasingly being recognized in major global fora, such as the UNFSS and the UNFCCC. However, the sustainability situation of marine capture fisheries remains a concern, despite noticeable improvements in several regions. The fraction of marine fishery stocks within biologically sustainable levels decreased 2.3 percent between 2019 and 2021, to 62.3 percent (FAO 2024a). When weighed by production levels (e.g. where one fish stock is a population and a % of stock is caught), an estimated 76.9 percent of 2021 landings from FAO-monitored stocks were from biologically sustainable stocks (FAO 2024a). Effective fisheries management is instrumental in stock recovery (Hilborn *et al.*, 2020) and is critical to maintaining and rebuilding healthy fish stocks, especially given the accelerating impacts of climate change.

8.1.1 OBSERVED IMPACTS ON FISH ABUNDANCE AND DISTRIBUTION

Ocean warming is believed to be responsible for a 4.1 percent decline in the combined maximum sustainable yield of 235 global fish and invertebrate populations (around 33 percent of reported global catch) over the past 80 years (they decreased from 35.2 Mt in 1930—1939 to 33.8 Mt in 2001—2010) (Free *et al.*, 2019). Moreover, temperature is driving changes in fish body size, with species-dependent impacts. For example, an analysis of 10 million visual survey records across the Australian continent and multiple decades found that 55 percent of coastal reef fish species (335 species) were smaller in warmer waters, while 45 percent were larger (Audzijonyte *et al.*, 2020). Impacts of increased temperatures and reduced oxygen content are also described in the Humboldt current, one of the world's most productive fishing areas, where a paleobiological analysis finds that small-sized species seem to be favoured as environmental conditions change (Selvatecci *et al.*, 2022). Intra-annual sea surface temperature variation also impacts annual marine fisheries catches. Research indicates that a 1 °C increase in intra-annual sea surface temperature variation is associated with a 12 percent increase in catches for low- and high-latitude aseasonal countries, but a 30 percent decrease in catches for highly seasonal mid-latitude countries (Hume *et al.*, 2024).

Moreover, marine species are undergoing distributional shifts at a faster rate than terrestrial species, with an observed range shift of 72 km per decade between 1960 and 2009 (Poloczanska *et al.*, 2013). These distributional changes have contributed to an acceleration in the spread of aquatic non-indigenous or invasive species, impacting aquatic ecosystems and fisheries systems (Azzurro *et al.*, 2024; Bailey *et al.*, 2020). There is some evidence that climate change has enabled these species to expand into regions where they were previously not able to survive and reproduce; for instance, ocean warming has driven the range expansion of the long-spined sea urchin, impacting kelp-dominated reef ecosystems and affecting abalone fisheries in Tasmania (Keane *et al.*, 2024).

In addition, climate change is altering ocean oxygen content, with a reduction of at least 2 percent in the global inventory since the last century, with varying adverse effects on marine life and ecosystems over time and depending on region (Kim, Franco and Sumaila, 2023; Schmidtko, Stramma and Visbeck, 2013). For example, hypoxia was reported to have caused a 12.9 percent annual catch loss (worth USD 1.25 million) in North Carolina shrimp fisheries from 1999 to 2005 (Huang *et al.*, 2012).

BOX 8.1. New developments: hydroponic fodder production for reduced land competition and mitigation

The El Niño Southern Oscillation is a natural climate phenomenon that periodically causes warming (El Niño) or cooling (La Niña) of the Pacific Ocean, affecting weather patterns around the globe and driving extreme weather events, including drought, flooding and storms. El Niño events have been linked to changes in fish catch from a variety of fisheries, by altering species distribution, reducing habitats, and affecting fish reproduction and recruitment. For example, in 2023, because of El Niño, Peru saw a 50 percent reduction in industrial landings of Peruvian anchoveta, the world's largest monospecific fishery, compared with 2022 (FAO, 2024a; FAO, 2024d).

Beyond the El Niño Southern Oscillation, climate change is increasing the frequency, duration and intensity of marine heatwaves, compounding risks to aquatic food production (Free *et al.*, 2023). The 2014–2016 Northeast Pacific heatwave, the largest on record, caused extensive ecological disruptions. These included the loss of kelp forests and their associated abalone and urchin fisheries, harmful algal blooms that closed shellfish fisheries, increased humpback whale entanglements due to increased overlap of whale foraging grounds with the Dungeness crab fishery, and recruitment failures in several species (such as Pacific cod). Ecological benefits also posed management challenges. For example, surges in shortbelly rockfish, a non-target bycatch species, required urgent bycatch management to prevent Pacific hake fishery closures; the northward expansion of California market squid required swift regulation of new fisheries; and the influx of Pacific bluefin tuna into US waters boosted recreational fishing.

8.1.2 PROJECTED IMPACTS ON FISH ABUNDANCE AND DISTRIBUTION

Global projections indicate significant declines in exploitable fish biomass under an FAO high-emissions scenario that projects global warming of 3.0—4.0 °C (Blanchard and Novaglio, 2024). By mid-century, many regions are expected to face declines in excess of 10 percent, worsening to 30 percent or more in 48 countries and territories by the end of the century. In contrast, under a low-emissions scenario, where global warming is limited to 1.5—2.0 °C, changes stabilize between no change and a decrease of 10 percent or less across 178 countries and territories (Blanchard and Novaglio, 2024). In addition to climate change, fishing intensity impacts the rebuilding of fish biomass. Under a worst-case scenario combining 3.5 °C warming with overexploitation, biomass is projected to decrease to 36 percent of the current level across marine ecoregions (Cheung *et al.*, 2022). These compounding pressures underscore the need for effective fisheries management alongside strong climate change mitigation efforts.

The impacts of climate change are not limited to biomass declines; they also drive shifts in the distribution of transboundary fish stocks. According to Palacios-Abrantes *et al.* (2022), by 2030, 23 percent of transboundary stocks will have shifted and 78 percent of the world's exclusive economic zones will have experienced at least one shifting stock. The study further projects a total of 45 percent of stocks shifting globally by the end of this century and 81 percent of exclusive economic zone waters having at least one shifting stock. These shifts necessitate revisions to international fisheries agreements to minimize conflicts, address socioecological implications and enhance resilience through anticipatory measures.

What is more, projections from the Coupled Model Intercomparison Project indicate that, in the 2090s, oxygen levels in the global ocean will decrease by about 4 percent under the RCP 8.5 scenario and 2 percent under the RCP 2.6 scenario compared with the 1990s (Bopp *et al.* 2013). However, regional trends in oxygen loss projections are subject to uncertainty (Kim, Franco and Sumaila, 2023; Bopp *et al.*, 2013) and, while there are likely to be impacts on fisheries resources, these need to be explored further.

8.1.3 ASSESSING VULNERABILITIES

Without adaptation, these climate change impacts will threaten food provision, nutrition, health and livelihoods, as well as regional and global trade patterns.

Food security and safety: provision, nutrition and health

There is growing recognition of the importance of aquatic foods in food security and nutrition, not just as a source of protein, but as a unique provider of omega-3 fatty acids and bioavailable micronutrients. Aquatic foods include a diverse group of animals, plants and microorganisms, each with unique qualities and nutrients, such as iron, zinc, calcium, iodine, vitamins A, B12 and D, and omega-3 fatty acids (UN-Nutrition, 2021). Fish, particularly small fish, remain the most accessible, affordable or preferred animal-sourced food for many poor, rural populations.

Climate change may favour the presence of invasive alien species harmful to animal health and potentially increase the risk of disease outbreaks. Moreover, it can affect the occurrence of food safety hazards at various stages of the supply chain, posing significant challenges to food safety.

Social vulnerability, including gender and marginalized groups and cultural services

Climate change and disasters pose profound risks to food availability and access, in addition to health, housing and other basic needs, with disproportionate impacts on vulnerable groups (Cook, Rosenbaum and Poulain, 2021). Cultural services, such as the preservation of traditional knowledge and practices tied to fisheries, may also be threatened by climate change. These services support not only economic livelihoods, but also social cohesion and the identity of many small-scale fishing communities (Maharja, Praptiwi and Purwanto, 2023). Ensuring the integration of cultural considerations into climate adaptation and disaster response strategies is critical to safeguarding the well-being of these communities and maintaining the social and cultural fabric that underpins sustainable development.

Gender disparities further compound vulnerability to climate change. While men are often at higher risk of physical dangers, such as unsafe fishing conditions, women disproportionately bear the economic hardships arising from declining production and extreme weather (Wabnitz *et al.*, 2021). These gendered vulnerabilities stem from socioeconomic inequalities, power imbalances and restrictive norms that limit women's rights and decision-making opportunities. Despite gender equality being a key guiding element of the UNFCCC, fisheries adaptation policies often fail to adequately address gender disparities. Most of these policies lack clear strategies or actionable measures to empower women and tackle the underlying inequalities that heighten their vulnerability to climate change (Gopal *et al.*, 2017).

Management, economic and geopolitical vulnerabilities

Current fisheries management systems are largely unprepared to address climate-related impacts such as shifts in fisheries productivity and distribution (Bahri *et al.*, 2021; Bell *et al.*, 2020; Holsman *et al.*, 2020). Many remain reliant on principles of stationarity, including in population parameters used in models, leading to misalignment between management measures (such as quota allocation and fishing areas) and the evolving conditions of fish stocks, causing delays in or an absence of management action, with impacts on fisheries sustainability. Moreover, climate change is likely to increase conflicts among fishery users and authorities, as well as nations sharing fishery resources, potentially heightening disputes in addition to creating opportunities for cooperative management (Mendenhall *et al.*, 2020).

Furthermore, climate change presents substantial economic risks for countries and regions heavily reliant on fisheries revenue. For instance, in Pacific Small Island Developing States (SIDS), projections indicate that under a high GHG emissions scenario (RCP 8.5), the biomass of three key tuna species in the waters of ten Pacific SIDS could decline by an average of 13 percent by 2050, and this is expected to reduce purse seine catches by 20 percent, resulting in an average annual loss of USD 90 million in tuna fishing access fees (Bell *et al.*, 2021).

8.1.4 ADAPTATION

The accelerating impacts of climate change and the high vulnerability of fisheries to such impacts highlight the urgent need for adaptation actions to be implemented at scale, with robust financial support to fill the adaptation finance gap of around USD 4.5 billion per year by 2030 for the fisheries and aquaculture sector (FAO, 2024b). Adaptation policy frameworks for resilient fisheries exist, including the FAO Adaptation Toolbox for fisheries and aquaculture (Poulain, Himes-Cornell and Shelton, 2018), early adaptation frameworks and adaptation policy cycle (Watkiss, Ventura and Poulain, 2019), and guidance on good practices to climate-proof the fisheries management cycle (Bahri *et al.*, 2021). Building on these frameworks, FAO is implementing a field programme of adaptation projects in more than 20 countries in Africa, Asia Pacific and Latin America and the Caribbean to support vulnerable fisheries and aquaculture communities. Examples of key activities include strengthening information management and monitoring capacities, improving safety at sea, enhancing policy and legal frameworks, diversifying livelihoods and integrating gender issues.

An effective fisheries management system is often the best adaptation and the first foundation of climate-resilient fisheries (Bahri *et al.*, 2021). Projections suggest that climate-adaptive fisheries management can increase the global fisheries catch under moderate climate change, though not uniformly across all countries (Free *et al.*, 2022). Proven good practices adaptable to various contexts include, for example, flexible fishing seasons, early warning systems for slow-onset and extreme events, such as El Niño and marine heatwaves, and tradable fishing rights or allocations responsive to transboundary stock shifts (Bahri *et al.*, 2021; Bell *et al.*, 2021; Free *et al.*, 2023). Regional fisheries management organizations and advisory bodies are increasingly aware of the challenges posed by climate change, and some have initiated actions such as awareness-raising initiatives, policies, management plans and projects, while recognizing the need for a better understanding of the impacts on distribution and productivity of the shared stocks they govern (FAO, 2023a, 2024c).

When it comes to managing the risks of aquatic non-indigenous or invasive species, prevention is the first line of defence. Nevertheless, eradication is often impractical once they establish, necessitating adaptive management strategies. Recognizing their negative impacts on natural ecosystems, some have been commercially exploited, which may compensate for the decline in thermally sensitive natives with similar traits (Azzurro *et al.*, 2024; Katsanevakis *et al.*, 2023). Adaptive management practices learned from global case studies include developing commercial fisheries, encouraging recreational harvesting, exploring market opportunities, implementing outreach programmes, engaging stakeholders, applying spatial and biological controls, and restoring ecosystems (Azzurro *et al.*, 2024).

8.1.5 MITIGATION

Fisheries are estimated to have one of the lowest carbon footprints of animal-source food commodities (MacLeod *et al.*, 2020; Gephart *et al.*, 2021). They contribute less to global carbon emissions than many other maritime activities, such as shipping (IMO, 2020). Despite this, the sector is often overlooked in mitigation discussions, leaving decarbonization opportunities untapped. Data on post-harvest emissions from processing, distribution, transportation and marketing remain limited (Cochrane *et al.*, 2024). Key opportunities include adopting renewable energy technologies, such as biogas engines and solar photovoltaic systems for storage, lighting and powering fishing vessels (UNCTAD, 2024; Puri *et al.*, 2023).

8.2. ILLUMINATING AVOIDED GHG EMISSIONS FROM INLAND FOOD FISHERIES

A new FAO study draws attention to the role and potential of inland fisheries as a source of low-emission animal-protein food in avoiding GHG emissions, but their invisibility in relevant policies and investment (FAO, 2025). Comparative GHG impacts of goods (or services) are estimated as the difference between the life-cycle GHG inventory of an assessed product and an alternative reference product that provides an equivalent good (or service). Where the assessed product emits less over its life cycle than the reference product, the difference is referred to as "avoided emissions" — the subject of much attention in climate change mitigation (for example, renewable energy to replace fossil fuels or shifting food systems to lower GHG footprints are both about avoided emissions). According to World Resources Institute guidelines (Russell, 2018), avoided emissions can be represented in goods and services already being produced ("attributional" in GHG accounting) or estimated based on projections of a future action or change in policy or investment ("consequential" in GHG accounting). The two are interrelated for inland food fisheries, because although there can be potential to improve production (through improved management and ecosystem restoration), overall, they are currently in decline and highly threatened. For example, production from the world's largest inland fishery in the Lower Mekong River Basin has declined by 30 percent in the last two decades and a further 40 percent reduction is predicted in the near term (Mekong River Commission, 2024). As a result, changes in policy and investment (consequential avoided emissions) are required to sustain current production (attributional avoided emissions).

The reference for inland food fisheries is livestock, using protein equivalent as the common denominator. In other words, losses in fisheries, or potential increases, are most likely to be compensated for, or produced by, livestock alternatives. In principle, plant-based proteins provide a logical (and sometimes low-emission) alternative, but realistic comparisons must consider likely trends for increased production of animal-source protein. Marine fisheries (with higher emissions than inland fisheries, but still lower emissions than livestock) are not a viable reference, as they are considered globally fully or over-exploited. Reliable comparative assessments for aquaculture as a whole are not available. While some systems have low emissions, others have higher emissions than for livestock, and current information suggests that, overall, the sector may have equivalent emissions to livestock.

Comprehensive data for reference livestock are available (FAO, 2023b). Emissions vary widely between commodity and production methods. For comparative purposes, "combined" emission intensity (using CO_2e per kg of protein) can be used, namely, total emissions from all of the sectors divided by total protein production. This varies from region to region and, when used as the reference, assumes that the composition of commodities and methods of production will be stable. Reference livestock data are disaggregated by source of emissions across the life cycle of and emissions from the same life-cycle components. Any others can be estimated for inland food fisheries for comparison. The bulk of catches from inland food fisheries come from low- or zero-energy, small-scale, non-motorized gears, using either no vessels or predominantly non-motorized vessels. Catches are mainly consumed locally, so require little energy for transport and processing and, importantly, do not emit CH_4 – the major source of GHG with livestock. Exceptions for individual fisheries exist, although these emissions are still comparatively low. Overall emissions intensity for inland food fisheries is negligible compared with a livestock reference.

The total current reported global production of inland fisheries (about 11.5 Mt/yr) represents about 215 Mt/yr of avoided emissions (CO_2e), about 3.5 percent of total combined emissions from livestock. Based on a European Union reference carbon market price, this corresponds to a monetary value of about USD 20 billion per year. These are significant values, but global comparisons include areas with high livestock production and limited inland food fisheries (such as North America and Europe). Relative GHG emissions avoided depend on the extent of inland fishery production and overall national GHG emissions. Case studies for a number of countries with significant inland food fisheries provide more meaningful comparisons. These range from about 3.5 percent to 17 percent of national GHG emissions from energy and industry avoided for inland fishery production for Viet Nam and Cambodia, respectively, among sample countries in Asia, and between 66 percent and 184 percent for the United Republic of Tanzania and Malawi, among sample countries in Africa (where higher values are in part due to higher inefficiencies in livestock production and lower total national GHG emissions). The results highlight the need to recognize the value of avoided GHG emissions from inland capture fisheries in policy, planning and investment, and can provide a strong case for accessing carbon financing to support their sustainability and achieve sustainable food production systems. These avoided emissions come on top of other co-benefits of inland fisheries, including their high value for food and nutrition security, poverty reduction and livelihoods. In contrast to livestock, although inland fisheries are vulnerable to land-use change, they do not cause it and are non-polluting. They are a co-benefit of mainly natural or semi-natural ecosystems, notably wetlands, which deliver a wide range of other supporting and regulating ecosystem services, many of which also have high value for climate change mitigation and adaptation.

8.3. OVERVIEW OF AQUACULTURE

Aquaculture production has expanded in recent decades to meet global food and nutrition security needs (including protein and micronutrients) and provide other valuable products to the growing human population (Jiang *et al.*, 2022), particularly in developing countries (Béné *et al.*, 2016). In 2022, for the first time, aquaculture surpassed capture fisheries in aquatic animal production, accounting for 51 percent of the world total and 57 percent of production for human consumption (FAO, 2024).

In 2017, aquaculture (including all shellfish and finfish aquaculture) was estimated to be responsible for 263 $MtCO_2e$, or 0.49 percent of total anthropogenic emissions (Macleod *et al.*, 2020). For instance, by 2030, aquaculture is projected to generate more than 5 percent of total anthropogenic N_2O emissions (Hu *et al.*, 2012; Paudel *et al.*, 2015). In the absence of effective mitigation strategies, the global significance of aquaculture GHG emissions is expected to rise with production intensification (Yuan *et al.*, 2019).

With aquaculture's growth, strategic plans become essential in defining how to mitigate GHG emissions and promote resilience to climate change risks. However, uncertainties surrounding GHG emissions and removal estimates from aquaculture systems production remain high. There is a wide range of GHG emissions among different species and systems (Gephart *et al.*, 2021), requiring more research and development to establish emissions/removal factors to support the shift to more sustainable practices and systems.

Technological innovations that improve production efficiency, directly alter water chemistry and use ecosystem-based approaches are needed to mitigate emissions from aquaculture. Technologies to improve production efficiency in aquaculture are often implemented to save costs by reducing the energy, materials, waste, and land and water area required to bring a given quantity of product to market. Novel product, process and equipment technologies provide management interventions that alter water or sediment chemistry to increase stocking density, improve product quality, reduce environmental impacts and buffer aquaculture from external conditions. Ecosystem-based approaches take advantage of natural processes. Efficient farming practices and techniques can lower GHG emissions associated with aquaculture.

Technologies for GHG mitigation outside the aquaculture facility (that is, pre- and post-farm gate) are like those for terrestrial agriculture, and consider energy use, land use and change for producing feed, processing, transportation and waste management. Opportunities for technological intervention at the aquaculture facility are generally sector specific. Across all stages, incorporating elements such as energy-efficient pumps, vehicles, tools and lighting will mitigate GHG emissions. Recent technological advances with high potential for mitigation are described in Section 8.3.1, which gives more detail on opportunities on the farm.

8.3.1 TECHNOLOGICAL ADVANCES IN AQUACULTURE FOR MITIGATION

Aquafeed production and use

Aquafeed production and use is a major contributor to emissions from aquaculture — around 0.15 $GtCO_2e$/yr (MacLeod *et al.*, 2020). Strategies that incorporate ingredients with low carbon footprints and integrate renewable energy sources to power feed processing and transport can be solutions. Choosing more efficient aquafeed production processes, which bring greater productivity and lower GHG emissions, can fit into mitigation options for fed aquaculture. For example, the estimated footprints of extruded and pelleted aquafeed are 1,334 $kgCO_2e$/t and 1,071 $kgCO_2e$/t, respectively, indicating that using pelletized aquafeed over extruded feed could save 263 $kgCO_2e$/t (Wang, Cheng and Liu, 2022). Where aquafeed ingredients are sourced from also matters, with emissions from both extruded and pelletized feed reduced by 15 percent by changing the source location of soybeans used to produce the feed (Wang, Cheng and Liu, 2022a).

Feed conversion ratios can be improved in several ways, mitigating GHG emissions and reducing costs by lowering feed input requirements (MacLeod *et al.*, 2019). Best feeding management practices consider the timing and quantity of feeding for a given species under farm-specific conditions. A decrease in the feed conversion ratio can lead to a reduction in GHG emissions, stemming from both fewer food inputs and the diminished release of nutrients used in GHG production into water and sediments (Moberg *et al.*, 2022). Precision nutritional regulation further refines feeding management through the use of sensors and computers to optimize feeding times and quantity (Mandal and Ghosh, 2024). Additives can improve palatability, nutritional value and the digestibility of feeds, reducing waste and input requirements (Hossain *et al.*, 2024; Serra *et al.*, 2024). Genetic improvements of cultured species, such as through selective breeding, hybridization and, potentially, gene editing, can also improve efficiency by changing fish diet preferences and requirements, and by improving the incorporation of food, in addition to other efficiency improvements (Overturf, Barrows and Hardy, 2013; Brezas and Hardy, 2020; Pacheco *et al.*, 2025).

Fishmeal and fish oil are being replaced by terrestrial (animal- and plant-based) ingredients in aquafeed, though how such a change influences aquafeed emissions is unclear. LCAs suggest that aquafeed using fishmeal from fisheries has about half the emissions footprint of terrestrial sourced feeds (see, for example, Newton *et al.*, 2023). However, such assessments do not include emissions from fisheries-induced changes to ecosystem processes that disturb carbon cycling (Andersen *et al.*, 2024; Ray *et al.*, 2025). For example, incorporating emissions associated with sediment disturbance yielded a 6-fold to 500-fold increase in the CO_2 footprint of a fishery in the Mediterranean Sea (Muñoz *et al.*, 2023). Much needs to be done to understand the most significant points of impact throughout the aquafeed production and use processes to facilitate mitigation, including a more thorough accounting of emissions associated with fisheries ingredients. With technological improvements in production processing, fishmeal and fish oil from by-products are attractive to the market due to their circularity and lower carbon footprint, aiding mitigation.

Site selection

Constructing aquaculture ponds on degraded lands or installing cage mariculture away from blue carbon ecosystems (such as mangroves, salt marshes and seagrass meadows) provides an opportunity for food production while minimizing carbon emissions associated with deforestation or habitat destruction (Jones *et al.*, 2022; Li *et al.*, 2025; Pacheco *et al.*, 2025). Locations with stronger currents can help to maintain dissolved oxygen levels within cage or line facilities, improving animal health and reducing the effects of aquaculture on CH_4 production (Jones *et al.*, 2022). They can also allow for higher stocking density, reducing the area needed to raise a given amount of product (FAO, 2022). Balancing the location of aquaculture in areas that reduce emissions and the stress of animals and seaweeds with financial and social considerations is a key step in ensuring aquaculture sustainability.

Co-locating aquaculture with renewable energy generation

The installation of floating solar panels (or aquavoltaics) at an aquaculture facility can cool the water, serving as an adaptation measure for the cultivation of species sensitive to heat (Wang *et al.*, 2022). Aquavoltaics also offer on-site renewable energy production, reducing the need for fossil fuels and associated infrastructure, lowering emissions from the farm. One trade-off of aquavoltaics is reduced oxygen availability. This is associated with an almost doubling of ebullitive CH_4 emissions in non-aquaculture settings (Ray, Holgerson and Grodsky, 2024), and can also reduce animal growth and the feed conversion ratio, necessitating the use of other technologies, such as aerators. Similarly, co-locating aquaculture with offshore wind farms can reduce emissions by taking advantage of existing infrastructure for moorings, readily available renewable energy and well-oxygenated waters (Maar *et al.*, 2023). Additional examples of renewable energy interventions in aquaculture include biofuel-powered engines for equipment such as feeders, pumps, aerators and security lighting, as well as geothermal energy for heating fish ponds (Puri *et al.*, 2023).

Maintaining dissolved oxygen availability

Mechanical aeration is a management technique for maintaining water-column dissolved oxygen availability in aquaculture facilities for improved animal growth rates, better product quality and reduced risk of disease (Boyd, 1998). Oxygen availability is a key control on GHG production in aquaculture facilities, and mechanical aeration can reduce aquaculture pond CH_4 emissions by more than 50 percent by limiting methanogenesis (Fang *et al.*, 2022). Aeration may come at the cost of increased N_2O emissions, though there is disagreement in the literature on the direction of this effect, and even when N_2O emissions increase, aeration still reduces total pond emissions on a CO_2e basis (Hu *et al.*, 2013; Yang *et al.*, 2023). Powering aerators also has an associated GHG cost, though innovations in aerator design and performance mitigate these emissions (Aytac, Kelestemur and Tuna, 2024). Thorough accounting of aerator effects on emissions and the GHG cost of powering aerators is still needed for an accurate estimation of mitigation effects (Kosten *et al.*, 2020).

Sediments in aquaculture settings consume oxygen and produce GHGs due to high loads of organic material. Aquaculture ponds are occasionally drained and excess sediment removed to maintain pond volume and improve oxygen availability. Sediment removal reduces pond GHG emissions during the grow-out period, but emissions can be high during the drawdown period. Shortening the time between draining and refilling the pond can minimize this emissions pulse (Lai, Yang and Tong, 2021). Removed sediments continue to emit GHGs, though these emissions are not well quantified and can be offset by using removed sediments in agriculture (Haque *et al.*, 2016; Yang *et al.*, 2018a). Sediment removal eliminates any carbon burial in the pond.

Non-fed, low-input aquaculture and integrated systems

Non-fed and low-input aquaculture use food and nutrients from the surrounding ecosystem and have high productivity in areas with high nutrient loading, serving to both produce food and reduce the negative consequences associated with excess nutrient loading without the addition of aquafeed and its associated emissions (Barrett *et al.*, 2022; Jones *et al.*, 2022). For example, oyster aquaculture removes excess nitrogen loaded to coastal ecosystems and has a small emissions footprint of 0.13 $kgCO_2e$/kg protein produced (Ray *et al.*, 2019; Ray and Fulweiler, 2021). Seaweed aquaculture uses nitrogen and phosphorus from the water column while taking up carbon during photosynthesis. Because of this, seaweed aquaculture has drawn substantial interest as a potential strategy for large-scale carbon capture (Froehlich *et al.*, 2019; Duarte, Bruhn and Krause-Jensen, 2022). There is little doubt that seaweed farming can help reduce food-system emissions, but uncertainty as to the long-term fate of carbon fixed by seaweeds and the potential trade-offs associated with expansion of the sector need to be addressed before seaweed farming can be properly considered a globally useful carbon capture technology (Troell *et al.*, 2023; Chopin *et al.*, 2024; Cornwall, 2024).

Integrated multitrophic aquaculture (IMTA) uses waste from one farmed species as food for another. For example, seaweeds in IMTA settings use nutrients excreted by fish or bivalves, enhancing growth and carbon uptake, while bivalves can consume aquafeed not ingested by fish, in addition to fish faeces and/or phytoplankton that grow using nutrients excreted by fish, improving efficiency of the system and reducing emissions (Nederlof *et al.*, 2022). IMTA has been practised for millennia, and incorporating modern products, processes and equipment can further improve its efficiency (Goda *et al.*, 2024). Recirculating aquaculture systems are water efficient, so provide resilience in areas with increasing drought risk, but can have high N_2O emissions (around 1.2 gN_2O/kg fish produced) (Yogev, Atari and Gross, 2018), particularly in the portion of the system designed to remove excess nutrients (Hu *et al.*, 2012). Despite having lower emissions than intensive aquaculture systems, IMTA and recirculating aquaculture systems are complex to manage, requiring substantial technical knowledge and investment in capacity building.

Steps forward

Implementing mitigation technologies in aquaculture requires farmers to have access to information and funds, as well as equitable implementation that considers human health and livelihoods (Stanford Center for Ocean Solutions *et al.*, 2024; Pacheco *et al.*, 2025). A more thorough quantification of the appropriateness and effectiveness of various technologies across aquaculture species, practices, systems and locations is needed to properly determine which technologies will be most impactful (Ray *et al.*, 2025).

8.3.2 BIVALVE AQUACULTURE

Bivalve mollusks are crucial to both economic activity and food security in coastal regions. In the five years since 2019, bivalve aquaculture has seen remarkable advancements, with more than 915 scientific papers containing "bivalve" and "aquaculture" as research keywords published (based on a Web of Science search on 5 November 2024). These research papers focus on breeding techniques, disease management, genetic engineering, environmental monitoring and sustainability in bivalve farming practices in the context of climate change and related stressors. Considering the number of scientific contributions, it is difficult to provide a quantitative analysis of breakthrough or tipping points in science topics. While all the aforementioned topics have progressed well over the past five years, there is increasing interest in the scientific literature in promoting the resilience of the shellfish industry to climate change and other upcoming stressors. For instance, there is a growing consensus that global changes in coastal environments will negatively impact bivalve aquaculture (Clements and Chopin, 2017; Stewart-Sinclair *et al.*, 2020; Froehlich, Gentry and Halpern, 2018; Reid *et al.*, 2019; Galappaththi *et al.*, 2020). While concrete data on production gains or losses, specific locations and timelines are still lacking (Pernet *et al.*, forthcoming), adaptation strategies through the exploration of new technologies and sites, selective breeding and engineering, and nature-based solutions, such as co-culture with algae, are under way. In addition, in the context of efforts to reduce our carbon footprint and protect biodiversity, the sustainability of bivalve farming is attracting growing interest as a form of "blue food", a term gaining prominence in the scientific literature.

Adaptation to global change

Moving offshore

Bivalve growers are increasingly considering a move to the open sea to address the challenges posed by changing nearshore conditions (Long *et al.*, 2024). As climate change leads to extreme variations in nearshore temperature, oxygen, pH and salinity levels, the open sea offers more stable conditions that can support bivalve health and growth. Coastal waters are also becoming more prone to nutrient pollution and harmful algal blooms, driven by agricultural runoff and other human activities, which negatively impact water quality essential for bivalve cultivation. In contrast, offshore areas typically offer cleaner, well-circulated waters that improve growth conditions and reduce the spread of pathogens. The open sea also provides more space and potentially fewer conflicts with other coastal industries such as tourism, fishing and development, offering growers greater potential for expansion and higher yields. In addition, the development of wind farms may present new opportunities for offshore aquaculture, as these facilities could provide shared infrastructure and increased accessibility for bivalve farming in open waters (Maar *et al.*, 2023). While transitioning offshore presents challenges, including higher initial costs, exposure to storms and logistical complexities, the benefits of healthier bivalve stocks, faster growth rates and reduced disease pressures make it an attractive option for many growers. China, for example, has built over 40 deep-water aquaculture infrastructures, showing the potential for enhancing food security and aquacultural resilience. However, the current development trajectory primarily focuses on achieving profitability through high-value species and products rather than fully meeting the broader goals of sustainability and resilience (Dong *et al.*, 2024).

Selective breeding and genetic engineering

Another approach to bivalve farming is selective breeding. Selective breeding involves choosing organisms with favourable traits to reproduce, allowing them to pass on genetic advantages to future generations. This method accelerates adaptation compared with natural evolution, which takes much longer. While terrestrial agriculture relies heavily on genetically selected plants and animals, genetic selection in aquaculture has remained relatively limited (Sonesson *et al.*, 2023), especially in the case of bivalves, where it has remained at the experimental stage. Historically, selective breeding experiments conducted for bivalves have focused on traits that enhance survival, growth and meat yield or selection for shell traits (Jiang *et al.*, 2024). By breeding species with natural disease resistance, growers aim to develop bivalve lines that experience lower infection rates and reduced mortality. Recently, selective breeding has also been explored to help bivalves adapt to environmental challenges brought on by climate change, including warming and acidification (Tan, Zhang and Zheng, 2020; Nascimento-Schulze *et al.*, 2021). Bivalves bred to withstand these stressors can better thrive in unstable coastal ecosystems, ensuring a steady supply, even under challenging conditions. Because bivalve resilience to climate change is a complex trait influenced by multiple genes, modern genomic tools are gaining interest in selective breeding to enhance the precision and effectiveness of genetic improvements (Bitter *et al.*, 2019; Jiang *et al.*, 2024). However, this approach requires careful planning in terms of research, capacity building, long-term investment and assessment of the acceptability of such innovations.

Other genetic approaches are being explored. For example, the use of hybrid bivalves (for example, crossing different oyster species or cross-breeding), which is frequently employed for the genetic improvement of agricultural species, has shown potential to improve growth and survival, especially in oysters from areas with high disease prevalence or environmental fluctuation (Jiang *et al.*, 2024). Advances in gene editing tools, such as CRISPR, allow the targeting of specific genes associated with disease resistance and stress tolerance. While CRISPR application in bivalves remains in the early stages, research is under way, with potential applications in enhancing bivalve resistance to environmental stressors (Jiang *et al.*, 2024).

Nature-based solutions

Lastly, the third point is the emergence of nature-based solutions to increase the resilience and profitability of bivalve farming in an era of rapid change. Co-culture with algae has received the most attention by far (Kapsenberg and Cyronak, 2019; Young *et al.*, 2022; Edworthy, Steyn and James, 2023; Leal *et al.*, 2024). Through photosynthesis, macroalgae and marine plants lower acidity and increase calcium carbonate saturation during the day, offering a temporary refuge for shellfish in future acidified conditions (Falkenberg *et al.*, 2021). This solution, which is not that novel – China has a long history of co-culture of bivalves and macroalgae — has been scientifically evaluated recently in oyster farms and shows promise (Young *et al.*, 2022; Li *et al.*, 2021; Han *et al.*, 2020). What is more, the presence of vegetation increases dissolved oxygen levels, helping to mitigate the risks of hypoxia. Therefore, algae can effectively counter two of the "deadly trio" of climate threats — warming, acidification and deoxygenation.

An additional beneficial strategy is the return of shells to the sea to help mitigate acidification. The dissolution of calcareous shells potentially increases seawater alkalinity, converting dissolved CO_2 into bicarbonate and carbonate ions, thereby raising the pH (Waldbusser, Powell and Mann, 2013; Pernet *et al.*, 2024). Furthermore, this practice avoids the CO_2 emissions associated with shell incineration and promotes carbon sequestration. It also enhances the circularity, resilience and sustainability of the shellfish industry by repurposing shells that are currently considered waste, a topic that is gaining attention in the shellfish industry (Chary *et al.*, 2023).

Sustainability of bivalve aquaculture

Bivalve aquaculture is widely regarded as a sustainable form of food production due to its low environmental impact and minimal resource use. As filter feeders, bivalves require no supplemental feed, reducing the need for fishmeal or grain-based inputs, and they help improve water quality by filtering excess nutrients and pollutants (van der Schatte Olivier *et al.*, 2020). This process not only benefits local ecosystems, but also contributes to healthier coastal environments. In addition, bivalve farming does not rely on freshwater, making it more water efficient than land-based agriculture or other forms of aquaculture. With low energy requirements and the ability to support biodiversity by providing habitats for marine organisms, bivalve aquaculture presents a resilient and eco-friendly option for sustainable food production, particularly as coastal ecosystems adapt to climate change (van der Schatte Olivier *et al.*, 2020).

Although some studies have suggested that bivalves could act as CO_2 sinks, with a potential impact on climate change mitigation similar to terrestrial forests or seaweeds (for example, Tang, Zhang and Fang, 2011), potentially making this industry eligible for carbon credits, recent research challenges this idea. A study by Pernet *et al.* (2024) found that the concept is based on theoretical misconceptions and lacks support from observational and experimental evidence. However, cultivated bivalves are still among the lowest CO_2-emitting sources of animal protein (Gephart *et al.*, 2021; Naylor *et al.*, 2021), and their carbon footprint could be further reduced by returning their shells to the ocean or adopting co-cultures with algae to partially offset CO_2 emissions (see previous section; Pernet *et al.*, 2024). Efforts to address climate change should consider broader objectives, including the preservation of ecological health, ecosystem services and biodiversity. In this regard, the overall positive impact of bivalves on marine ecosystems makes them a valuable component of sustainable aquaculture (van der Schatte Olivier *et al.*, 2020; Pernet *et al.*, 2024).

An emerging concern in bivalve aquaculture is microplastic pollution, which poses significant risks to the sustainability of these systems (Song *et al.*, 2023; Zhou *et al.*, 2021). Various types of microplastic are frequently detected in farmed bivalves, and farming equipment such as mesh bags, nets and attachment tubes or cups also contribute to microplastic contamination of the surrounding seawater (Bringer *et al.*, 2021). This pollution has implications for the safety of bivalve products and, potentially, human health. The bivalve aquaculture industry is increasingly aware of the need to reduce plastic uses, and new materials, such as biodegradable substrates and anti-fouling coatings, are currently being explored to minimize plastic dependence and mitigate environmental impact (Zhou *et al.*, 2021).

8.3.3 UPDATE ON GREENHOUSE GAS EMISSIONS IN INTEGRATED RICE—FISH FARMING SYSTEMS

Development and effect of rice—fish systems

Integrated rice—fish (IRF) farming systems are ecological agriculture systems that co-culture fish with rice (Ahmed and Turchini, 2021)[23]. This farming system has been practised for nearly 6,000 years in East and South Asia and has seen significant global adoption (Ruddle, 1982). The benefits of IRF systems are numerous, contributing to both food security and environmental sustainability:

- The complimentary use of water and land resources produces both grains and aquatic products (such as fish and shrimp) high in protein for human consumption (Li, Y.F. *et al.*, 2023).
- Animal activity in IRF systems, including feeding and soil disturbance, stimulates nutrient release, making more nutrients available for rice plants, enhancing crop growth.
- The feed and excreta of animals can improve soil fertility and enhance sustainable crop production (Bashir *et al.*, 2020).
- Rice—fish systems can reduce nitrogen fertilizer loss through leaching, increasing nutrient efficiency and reducing environmental pollution (Fang *et al.*, 2023).
- Aquatic animals in IRF systems can help control pest attacks and weed populations in paddy ecosystems, reducing the need for chemical pesticides and promoting healthier ecosystems (Yu *et al.*, 2023).
- IRF improves biodiversity and fosters resilient, sustainable and productive agriculture.

To date, IRF systems have been implemented in about 40 percent of rice-producing countries globally (Li, Y.F. *et al.*, 2023). IRF farming systems now cover as much as 2.54 Mha, accounting for 22.7 percent of global inland freshwater aquaculture area and 2.45 percent of global rice paddy area (Yuan *et al.*, 2019; FAOSTAT, 2025a). What is more, the global land area suitable for IRF is estimated at about 143 Mha, with a potential to produce 143 Mt of aquatic products annually (assuming an aquaculture yield of around 1 t/ha/yr). This can not only help to meet global demand for fish and aquaculture products, but also conserve land and water resources. Specifically, it could reduce demand for land by 143 Mha and demand for water by 6,435 billion m^3 of water annually, assuming water use of 45,000 m^3/t in extensive pond systems (Verdegem, Bosma and Verreth, 2006).

Regionally, IRF systems are most prevalent in Asia (Bangladesh, China, India, Indonesia, Vietnam, among others), which accounts for more than 90 percent of global rice and aquaculture production (Cui *et al.*, 2023). This system has been adopted in other regions too, including Africa (Ghana and Nigeria), North America (the United States), South America (Brazil) and Europe (Spain and Germany). China is the largest rice and aquaculture producer in the world and a major area of IRF development. In 2022, China produced 27.1 percent of global rice and 56.0 percent of global aquaculture (FAO, 2024; FAOSTAT,2025a). The total IRF area in

[23] In this sub-section, "fish" refers to aquaculture species including fish, shrimp, crab and so on.

China increased to 2.99 Mha in 2023 from 1.50 Mha in 2015, accounting for 55.3 percent of the country's national freshwater aquaculture area (MARA, 2024). Notably, following the introduction of national policy support, the IRF area in China expanded at a rate of 0.19 Mha/yr from 2015 to 2023, 17.5 times the rate in 1998 to 2015 (MARA, 2024).

Methane and nitrous oxide emissions in rice–fish systems

IRF farming systems are becoming an increasing concern as an significant source of atmospheric CH_4 and N_2O emissions (Yuan *et al.*, 2019; Shen *et al.*, 2024). IRF farming systems have the highest CH_4 and N_2O emission rates of all freshwater aquaculture systems, followed by semi-intensive and extensive systems (Yuan *et al.*, 2019). Despite accounting for only 4.3 percent of global freshwater aquaculture production, IRF farming systems were estimated to have released 1.19 MtCH_4 and 0.102 MtN_2O in 2014, accounting for 19.7 percent and 27.8 percent of global freshwater aquaculture CH_4 and N_2O emissions, respectively (Yuan *et al.*, 2019). Using updated global datasets, including 88 measurements from 27 studies, CH_4 and N_2O emission inventories have been re-estimated, with the IRF area of each country preserved, except for China (Qian *et al.*, 2023). New observation-based, global values for CH_4 and N_2O emissions from IRF systems have been estimated at 1.50 MtCH_4 and 0.07 MtN_2O, accounting for 2.58 percent of CH_4 and 6.15 percent of N_2O emissions from global paddy fields, respectively (FAOSTAT2025b; Qian *et al.*, 2023). The top three countries for IRF CH_4 and N_2O emissions were China, Egypt and India, which together accounted for 93.8 percent of global CH_4 and N_2O emissions from IRF systems.

Properties and mechanisms of methane emissions from rice–fish farming systems

A substantial body of research on CH_4 emissions from rice–fish co-culturing systems has been conducted worldwide, particularly in Bangladesh, China, India and Vietnam. IRF has been shown to have complex impacts on CH_4 emissions due to its influence on soil organic matter, oxygen levels and microbial processes. Studies highlight both increases and decreases in CH_4 emissions, depending on specific conditions and practices. For instance, Datta *et al.* (2009) and Bhattacharyya *et al.* (2013) reported that the co-culture of rice and carp in southeastern India significantly increased CH_4 emissions by 26 percent and 74–112 percent, respectively. Similarly, IRF systems in Bangladesh were found to emit 32–37 mgCH_4/m²/h during the cropping season, 60–85 percent higher than monoculture rice systems (Frei *et al.*, 2007). Li, Xie and Ye (2023) further demonstrated a remarkable 369 percent increase in CH_4 emissions from rice–shrimp farming fields compared with conventional rice fields in Jianghan Plain, China. Several factors have contributed to these increases in CH_4 emissions. First, fish farming typically necessitates extended flooding periods and higher water levels than rice monoculture, creating prolonged anaerobic conditions conducive to CH_4 production (Guo *et al.*, 2020; Wei *et al.*, 2024). For example, rice–shrimp co-culture in China often involves two shrimp farming seasons, one preceding rice planting from March to June (Yan, 2022). In addition, IRF farming generally does not adopt an intermittent irrigation regime (at least one drainage), facilitating CH_4 production, but preventing CH_4 oxidation (Zhang *et al.*, 2022). Second, higher water levels, combined with animal oxygen consumption, reduce redox potential, fostering anaerobic conditions favourable to methanogenesis. A meta-analysis revealed that IRF decreased dissolved oxygen levels by 18 percent globally and that this was the dominant factor in the 29 percent increase in CH_4 emissions compared with rice monocultures (Cui *et al.*, 2023). Third, organic compounds (such as starch and protein) in animal feed remnants and faeces can be more easily decomposed into available substrates for CH_4 production. A meta-analysis by Yu *et al.* (2023) showed a 12.8 percent increase in soil organic matter in IRF systems, on average. Fourth, the increased biomass in rice under IRF systems facilitates greater CH_4 transport by way of aerenchyma tissue. For example, Yang *et al.* (2025) reported that rice-mediated CH_4 emissions accounted for 35.6 percent and 38.7 percent of total emissions from crab—rice and fish—rice systems, respectively. Fifth, bioturbation by animals can trigger bubble release and stimulate CH_4 emission through ebullition (Colina *et al.*, 2021; Dong *et al.*, 2024).

In contrast, some studies have demonstrated that IRF can reduce CH_4 emissions. For example, Zhan *et al.* (2008) reported a 6.17 percent reduction in CH_4 emissions during rice season in integrated rice—carp farming systems in Jianghan Plain, China. Similarly, Fang *et al.* (2023) found that transitioning from rice monoculture to rice—crayfish systems reduced annual CH_4 emissions from 456 to 392 kg/ha in the lower reaches of the Yangtze River, China. In addition, rice—crab co-culture in Northeast China was shown to decrease CH_4 emissions by 13.5 percent compared with rice monoculture with continuous flooding (Zhang *et al.*, 2022). Several mechanisms have been proposed to explain the reduction in CH_4 emissions in IRF systems. First, the aerenchyma tissue can also transport oxygen from the atmosphere into the root zone, in turn, promoting CH_4 oxidation and mitigating CH_4 emissions (Li, F. *et al.*, 2023). Second, aquatic animals in paddy fields can ingest weeds, algae and plankton, which reduces competition for oxygen and increases dissolved oxygen content in the water. Wang *et al.* (2023) noted this as a key factor in suppressing CH_4 generation. Third, animal activities can accelerate gas exchange at the air—water and water—sediment interfaces. This increases dissolved oxygen levels and reduces the sediment reduction zone, thereby inhibiting CH_4 production (Yu *et al.*, 2023). Luo *et al.* (2023) reported a 14.4–31.1 percent increase in water dissolved oxygen content in rice—crayfish systems due to the digging and foraging behaviour of crayfish. Fourth, frequent animal disturbance in sediments can prevent the formation of large gas bubbles and reduce CH_4 emissions via ebullition (Booth *et al.*, 2021).

The variations in CH_4 emissions across studies are primarily attributed to the spatiotemporal heterogeneity of IRF farming systems, specifically in terms of natural conditions (for example, soil and climate) and field management (for example, variety and density, farming time, water and nutrient management strategies) (Dai *et al.*, 2022; Ding *et al.*, 2020). Yu *et al.* (2023) highlighted that the impact of IRF systems on CH_4 emissions differs geographically, with reductions observed in East Asia, but increases in South Asia, largely due to higher temperatures and precipitation levels in South Asia that favour CH_4 production. Compared with natural conditions, field management practices exert more direct and complex influences on CH_4 emissions from IRF systems on both a regional and global scale. For example, Datta *et al.* (2009) found that IRF increased CH_4 emissions more significantly when planting rice *cv.* Varshadhan than *cv.* Durg, as the former produced a higher yield, leading to more photosynthetic exudates that serve as substrates for methanogens. Similarly, Luo *et al.* (2023) revealed that CH_4 emissions were in the order of: rice monoculture > rice—crayfish (Australian lobster) co-culture > rice—crayfish (America crayfish, low density) co-culture > rice—crayfish (America crayfish, high density) co-culture. This pattern was attributed to the higher disturbance intensity of American crayfish, which increased water dissolved oxygen and soil redox potential, thereby enhancing CH_4 oxidation. A global meta-analysis by Huang *et al.* (2024) further revealed that rice—fish co-culture generally increases CH_4 emissions, whereas rice—crayfish co-culture decreases them, primarily due to opposing effects on sediment redox potential (rice–fish: –25.6 percent; rice–crayfish: +7.20 percent). Water and fertilizer management also play crucial roles in regulating CH_4 production and emissions in IRF systems. By compiling CH_4 emission data from global IRF systems, Ding *et al.* (2020) proposed that it would reduce CH_4 emissions when water levels were below 11.5 cm, but increase CH_4 emissions when water levels exceeded 11.5 cm, with the maximum enhancement occurring at a 25 cm water depth. In addition, Wang *et al.* (2024) found that CH_4 emissions from IRF farming systems increased more than fourfold when the feeding rate (the feed amount per unit body weight of fishes) reached 8 percent, mainly due to a substantial rise in methanogen abundance, which promotes methanogenesis.

Properties and mechanisms of nitrous oxide emissions in rice–fish farming systems

Similar to CH_4, IRF farming has shown diverse effects on N_2O emissions. Zhan *et al.* (2008) found that IRF increased N_2O emissions by 3.5 percent compared with rice monoculture. Similarly, Sun *et al.* (2019) reported a 16.8–21.0 percent increase in N_2O emissions from rice–crayfish systems than from rice monoculture systems in the Jianghan Plain, China. Liu *et al.* (2023) revealed that rice–prawn co-culturing systems release 1.78–2.21 kgN_2O/ha/yr, which was 14.1–41.7 percent higher than that from rice monoculture systems in southeastern China. Globally, IRF farming increased N_2O emissions by 16.1 percent compared with rice monoculture, based on a meta-analysis (Sun *et al.*, 2021). Such positive effects of IRF farming on N_2O emissions can be attributed to the following. First, the excretions of aquatic animals generally contain high concentrations of ammonium and decomposable organic carbon, providing carbon and nitrogen substrates for nitrification, as well as denitrification, thereby enhancing N_2O emissions (Liu *et al.*, 2023; Wang *et al.*, 2023). Second, the activity of benthic aquatic animals (especially benthivorous) stimulates microbial respiration, promoting benthic mineralization and releasing more nitrogen substrates into the water and sediment (Braeckman *et al.*, 2010). Third, bioturbation caused by animals (especially zooplanktivorous) promotes gas exchange between the atmosphere and water, leading to fluctuations in redox potential that stimulate N_2O production through nitrification and denitrification (Gao *et al.*, 2023).

In contrast, other studies have reported reduced N_2O emissions in IRF systems. Bhattacharyya *et al.* (2013) observed significant reductions in N_2O emissions, ranging from 7.87 percent to 12.36 percent, in rice co-cultures with different fish species (for example, mrigal, rohu, common carp and catla) in southeastern India. Similarly, rice–crayfish co-culture was found to reduce N_2O emissions by 31.9 percent and 33.3 percent compared with rice monoculture in the lower reaches of the Yangtze River and Jianghan Plain, China, respectively (Fang *et al.*, 2023; Li, Xie and Ye, 2023). In northeastern China, rice–crab co-culture reduced N_2O emissions by 16.7–28.2 percent during the rice-growing season (Wang *et al.*, 2019; Zhang *et al.*, 2022). Meta-analyses have also suggested that IRF farming reduces N_2O emissions by 12–32 percent compared with rice monoculture globally (Cui *et al.*, 2023; Huang *et al.*, 2024). The potential mechanisms for these reductions are: i) aquatic animals feeding on phytoplankton, which suppresses photosynthesis and lowers dissolved oxygen levels, creating reductive conditions that inhibit nitrification and nitrate availability for denitrification, thereby reducing N_2O production (Datta *et al.*, 2009; Lauerwald *et al.*, 2019; Dong *et al.*, 2024); ii) dissolved oxygen depletion in bottom water and soil due to animal respiration, which can promote the reduction of N_2O to N_2 through complete denitrification (Mermillod-Blondin and Rosenberg, 2006; Chapuis-Lardy *et al.*, 2007); and iii) enhanced nitrogen-use efficiency in the IRF systems, which can limit the accumulation of nitrogen fertilizer in sediment. Bhattacharyya *et al.* (2013) found that rice-fish co-culture decreased ammonium and nitrate concentrations and reduced the populations of nitrifying and denitrifying bacteria, which suppressed both nitrification and denitrification processes, further reducing N_2O emissions (Lauerwald *et al.*, 2019).

Conclusion

The IRF culture is a long-established and sustainable farming practice that optimizes land and water resource utilization, enhances production efficiency and mitigates agricultural pollution by promoting nutrient and matter recycling. Ahmed and Turchini (2021) highlighted that global adoption of the IRF system in 50 percent of rice fields could boost annual fish and rice production by 27 percent. However, despite its environmental benefits, IRF systems are also significant sources of GHGs, emitting 1.50 $MtCH_4$/yr and 0.07 MtN_2O/yr. As one of the largest sources of GHGs in aquaculture systems, there remains substantial uncertainty as to the full extent of IRF farming's impact on GHG emissions from rice fields. To minimize the climate impact of IRF systems and provide lower-GHG food sources, it will be essential to develop appropriate field management strategies. Future research should explore diverse IRF farming systems, incorporating various planting and breeding patterns across different regions, to better understand the role of IRF in climate impacts. Such studies will also lay the foundation for creating IRF systems with better emission-reduction capabilities and greater environmental sustainability. Moreover, strong governmental and non-governmental support, including policy initiatives and technological guidance, will be crucial to promoting the widespread adoption of this practice.

8.3.4 UPDATE ON GREENHOUSE GAS EMISSIONS AND REMOVALS FROM AQUACULTURE PONDS

Aquaculture ponds and GHG emissions and removals

Among various production systems, aquaculture ponds are the most commonly used facilities for aquatic food production (FAO, 2024). However, the rapid expansion of aquaculture ponds has raised environmental and climate-related concerns (Williams and Crutzen, 2010). These shallow systems, if not well managed, can be considered a source of GHGs to the atmosphere, contributing more than 80 percent of all GHGs emitted by the aquaculture sector (Yuan *et al.*, 2019).

While aquaculture ponds emit significant amounts of CO_2 into the atmosphere (Aimé *et al.*, 2018), the CO_2 released from aquaculture ponds originates from recently fixed CO_2 (either from organic fish feed or primary producers in the pond) and is not considered an anthropogenic emission (Lovelock *et al.*, 2019). In contrast, the emissions of CH_4 and N_2O from aquaculture ponds are of major concern due to their high GWPs, which are, respectively, 34 times and 298 times higher than CO_2, over a 100-year time horizon (Myhre *et al.*, 2013).

Over the past 30 years, driven by the global boom in aquaculture, the number of scientific publications on GHG emissions from aquaculture has increased exponentially, reaching nearly 600 published papers in 2022, suggesting this is a topic of growing concern (Chen *et al.*, 2023). Data on the issue of aquacultural emissions currently come from all over the globe, with the majority stemming from Asia, particularly China. Africa is the most underrepresented continent in the literature, while Europe and South America also appear to be poorly covered.

Pathways of GHG emission and removals in aquaculture ponds

Life-cycle GHG emissions associated with aquaculture are mostly related to feed production, juvenile production, pond fertilizer, energy use, on-farm fuel use, land-use change, pond emissions and transportation. The majority of the life-cycle emissions are associated with land-use change for producing plant-based protein incorporated into feed. Among the different sources of emissions, the direct GHG emissions from aquaculture ponds are often neglected (Kosten *et al.*, 2020).

However, aquaculture ponds can directly emit GHGs through several pathways. The most widely recognized pathway is diffusive emission, a process in which dissolved gases move from areas of higher concentration to lower concentration, influenced by water-surface turbulence. The second pathway is ebullition, which occurs when CH_4 produced in low-oxygen sediment becomes saturated and forms bubbles that rise through the water column and release CH_4 into the atmosphere. Despite being examined in less than 10 percent of available publications, ebullition can be the dominant emission pathway in aquaculture ponds (Vroom *et al.*, 2023). The third emission pathway occurs during the draining-refilling cycle of the typical aquaculture pond (Yang *et al.*, 2015, 2018a)[24], particularly when the sediment remains moist, creating favourable conditions for N_2O and CH_4 production due to incomplete denitrification of the substrate (Hu *et al.*, 2013) or a rapid increase in microbial activity within the substrate (Birch, 1958)[25,26]. Emissions from the draining-refilling cycle, especially during the dry period, are often overlooked in the literature, and the magnitude of their contribution to total GHG emissions remains unclear. However, there is evidence suggesting that emissions in the dry period can be up to 100 times higher than when the pond is filled, and that appropriate management of the sediment can help to decrease GHG emissions from dry sediment (Yang *et al.*, 2015).

In addition, as in any aquatic ecosystem, carbon can accumulate in the sediment, which is a process of carbon removal. Aquaculture ponds can sequester carbon when primary production exceeds CO_2 production or when the ponds retain allochthonous carbon in the sediment (Chen *et al.*, 2016; Flickinger *et al.*, 2020; Zhang *et al.*, 2020). Annually, about 16.6 MtC is buried in aquaculture ponds, which is around 50 percent of the amount sequestered by natural lakes and inland seas (Boyd *et al.*, 2010). In such cases, aquaculture ponds act as an anthropogenic carbon sink (Adhikari, Lal and Sahu, 2012; Boyd *et al.*, 2010; Flickinger *et al.*, 2020).

Drivers of greenhouse gas emission and sequestration

GHG emissions from aquaculture ponds are driven by a complex interplay of factors related to nutrient inputs, biological processes, environmental conditions and management practices (Chen *et al.*, 2023; Kosten *et al.*, 2020; Munguti *et al.*, 2021; Vroom *et al.*, 2023; Xu *et al.*, 2022). Nutrient input from feed, fertilizer and manure increases organic matter accumulation in pond sediment, contributing to CH_4 and N_2O production and emissions (Chen *et al.*, 2023; Kosten *et al.*, 2020; Munguti *et al.*, 2021). In addition, microbial activities during decomposition, methanogenesis, nitrification and denitrification are key biological processes that drive CH_4 and N_2O formation.

24 Aquaculture ponds can be managed through various practices, including draining and refilling; draining, dredging the sediment and refilling; or draining, dredging, refilling and managing the dredged sediment.

25 Incomplete denitrification occurs when nitrate is partially reduced, leading to the release of N_2O instead of nitrogen gas.

26 Metabolic process carried out by microorganisms living in the substrate.

The quality of water and sediment also contributes to GHG formation and emission. Low oxygen levels promote anaerobic processes, such as methanogenesis, increasing CH_4 emissions (Yuan *et al*., 2019). Conversely, high dissolved oxygen levels, often achieved through aeration, can stimulate CH_4 oxidation and reduce overall CH_4 emissions, but may increase N_2O emissions (Yang *et al*., 2023). High water temperatures enhance microbial activity and GHG production, while simultaneously reducing gas solubility and increasing GHG emissions (Chen *et al*., 2023; Yang *et al*., 2018b). Additional drivers such as pH, salinity and nitrate are well documented in the literature (Kosten *et al*., 2020; Yang *et al*., 2023). In the sediment, organic matter accumulation, substrate quality and sediment depth affect microbial activity rates and GHG production (Chen *et al*., 2023; Kosten *et al*., 2020; Vroom *et al*., 2023).

Aquaculture management practices also play a crucial role in regulating GHG production. For instance, the prevention of overfeeding and excess fertilization and the appropriate management of the sediment can reduce GHG emissions (Munguti *et al*., 2021; Vroom *et al*., 2023). High fish-stocking density leads to increased nutrient loading and GHG emissions (Chen *et al*., 2023). Moreover, aeration has a complex impact on GHG balance; while it can help mitigate CH_4 emissions by increasing dissolved oxygen and enhancing CH_4 oxidation, it can also boost N_2O emissions (Yang *et al*., 2023; Zhang L.L. *et al*., 2024). In addition, the physical turbulence created by aeration can increase the diffusive flux of GHGs (Yang *et al*., 2023). Lastly, reducing feed waste and properly managing pond sediment can decrease organic matter accumulation, thereby lowering GHG production and emissions (Kosten *et al*., 2020).

Pond construction and greenhouse gas budget

The land-use change for the construction of aquaculture ponds determines the overall impact on carbon sequestration and emissions (Hu *et al*., 2016; Pacheco *et al*., 2025). Converting carbon-rich aquatic ecosystems, such as mangroves and wetlands, into aquaculture ponds helps to aggravate climate change (Zhang Z. *et al*., 2024). In tropical regions, the conversion of forests to ponds results in a higher GHG footprint than transforming degraded pastures into ponds (Pacheco *et al*., 2025). Therefore, accurately assessing the carbon budget by considering land use changes is essential for estimating net carbon emissions and GHG footprint from aquaculture ponds.

Conclusion

In recent decades, significant progress has been made on understanding GHG production and emissions from aquaculture ponds. Today, the relatively low climate impact of aquaculture compared with other animal protein production is known, and some management practices that can further reduce emissions from aquaculture ponds have been suggested. However, several challenges remain. There is a need to improve the existing database on CH_4 ebullition and N_2O emission, as well as data on emissions in the dry period. What is more, the impact of recirculated aquaculture systems on GHG emissions and sequestration needs to be further explored. Globally, it is essential to generate data for underrepresented regions, such as Africa and areas of Europe and South America. Lastly, it is crucial to advance with new management and technologies that can mitigate emissions throughout the entire production chain, with a particular focus on the pond production phase to reduce the carbon footprint of aquaculture.

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9. Technological advances

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9.1. REMOTE SENSING IN MONITORING, REPORTING AND VERIFICATION FOR LAND COVER, SOILS AND LAND MANAGEMENT

9.1.1 CONTEXT

It is impossible to reach an understanding of the global dynamics of climate and soil unless all components are well characterized. In this respect, multifaceted soil sensing techniques are powerful tools. The techniques cover many spectral ranges for identifying different soil properties and the equipment can be used at several sensing levels — proximal (laboratory, field, tractor) and remote (aeroplane or satellite) — as the principles remain the same regardless of scale. This makes it possible to upscale from farm to global level. Soil sensing is already equipped to gather multiple data sources on a global scale. The soil sensing community has matured since the year 2000. The Brazilian National Institute for Space Research has been delivering free CBERS satellite images since 2001. The European Space Agency is focused on mapping the world's soils from space and delivering free images from the Sentinel satellite for the global community. The US Department of Agriculture delivers temporal Landsat images from 1984 to present, and the US National Aeronautics and Space Administration (NASA), like many other national agencies, plans to launch new hyperspectral sensors worldwide. The bottleneck is the need for investment in human resources and processing. With data available, emerging AI and human knowledge, it is becoming easier to reach future goals. This unique topic provides a means of obtaining unparalleled amounts of information from soils, land use, climate, types of tillage and productivity.

9.1.2 ADVANCES IN SOIL ANALYSIS FOR ENVIRONMENTAL QUALITY: FROM LABORATORY TO FIELD SCALE

Soil remote sensing techniques have evolved exponentially in the last few years in response to growing demand for wet soil analysis in agriculture. The rationale for using soil sensing is to gain time, to lower cost, to be non-destructive and environmentally friendly (Peng *et al.*, 2025), and be applicable in any part of the world, including areas that are difficult to access. It can also bring together communities using the same languages and methods, as cloud computing can provide access to data from the field to the laboratory in seconds. In 2013 the Food and Agricultural Administration (FAO), led a pioneer meeting in Italy which initiated the construction of sensors for soil evaluation. On this basis, the Global Soil Laboratory Network, part of FAO's Global Soil Partnership, launched a project to create a global spectral library, with spectral data in the visible near-infrared and mid-infrared (mid-IR) range (FAO, n.d.). In 2021, the Triple E programme was launched to provide a protocol and certification for users of sensors for soil analysis. Since 2017, several worldwide initiatives have been collecting soil data and spectral information. The Land Use and Coverage Area Frame Survey project has been collecting data in 30 European countries (Orgiazzi *et al.*, 2018). The GEO-CRADLE initiative has gathered spectral data from nine countries in the Balkans, the Middle East and North Africa (Tsakiridis *et al.*, 2019), as well as others (Austria, Brazil, Czech Republic, China, Costa Rica, Denmark, France, Hungary, India, Indonesia, Mozambique, New Zealand, Poland, Spain, Switzerland and Tajikistan, plus Central and East African countries).

Spectral Libraries have concluded with the global soil spectral library (Viscarra Rossel *et al.*, 2016). Recently, other soil spectral libraries spanning large geographical areas have been developed (England and Viscarra Rossel, 2018; Dangal *et al.*, 2019). Energy and matter have a direct and specific relationship, making it possible to identify several soil properties (clay, sand, silt, cation exchange capacity, mineralogy, SOC, organic compounds, heavy metals and others). There are on-going commercial efforts to explore opportunities through the creation of hybrid soil wet laboratories that work together with information provided by sensors. Cloud computing is being developed via a pilot study where a soil can be analysed in real time at distance by using sensors (Demattê *et al.*, 2022). To date, several disciplines have employed soil sensing techniques (for example, soil, water, climate, plants, atmosphere and pollutants). Soil sensing is now being used in nearly all disciplines of soil science, from microbiology, specific carbon analysis, physics and heavy metals to chemistry and mineralogy, all of which are important actors in terms of carbon dynamics.

The need to press ahead with improved methods of carbon analysis goes hand in hand with the need for improvements in the calculation of soil carbon stocks. Rodríguez-Albarracín *et al.* (2023, 2024) demonstrated that soils with goethite and hematite have different stocks of carbon, despite the samples having the same clay content. Thus, it is not reasonable to use clay content alone in SOC stock calculations; the specific mineralogy should be used instead. This is where the power of soil sensing can be seen: detection and quantification of soil mineralogy can be achieved easily with soil sensing in a quick and non-polluted way. Many studies have shown that mid-IR can quantify carbon with great accuracy, even when correlated with combustion methods. The literature has shown that both methods agree with spectroscopy, so it is only a matter of calibration. Consequently, where combustion methods provide a good dataset, analysis can be linked with mid-IR, calibrated against this dataset and upscaled around the globe. The Rodríguez-Albarracín *et al.* (2023, 2024) studies detected mineralogy and its relationship with microorganisms by proximal sensing, which is of great significance in carbon identification, sequestration and dynamics. Other methods, such as laser-induced breakdown spectroscopy, have also been shown to achieve good results for carbon analysis (De Morais, McMeekin and Nault, 2024).

9.1.3 SOIL PROPERTIES FROM GROUND TO SPACE

Remote sensing (or EO) is a powerful tool, able to reach and detect any specific object and location on Earth. Once the object is identified, a spectral signature is created, which can then be analysed. If the position is in an area of bare soil, the detector can quantify carbon and other related soil properties. Das and Ghimire (2024) present several important advantages of remote sensing: it offers a temporal and spatial estimation of land cover, land management practices, cropping and tillage practices, net primary productivity and plant residues – all of which are critical for measuring and monitoring soil carbon sequestration and dynamics. Multivariate measurement of the soil reflectance in many spectral ranges can provide a cost-effective direct measurement of SOC, with extensive spatio-temporal coverage. With this, satellite imagery can also be used to assess changes in land use and agronomic practices, which can be used to verify and calculate carbon credits.

Even so, remote sensing has its limitations. Analysis has to be carried out on bare soil, and only surface data can be collected, although other strategies have been implemented, using vegetation, relief, climate, biome and other proxies to estimate soil parameters under these conditions. This is being enabled by AI, which can analyse large relational databases.

9.1.4 REMOTE SENSING TO ESTIMATE SOIL PROPERTIES FROM EARTH OBSERVATION

Spatial resolution is important to achieve accuracy when mapping SOC. Global data have to date reached their best performance at a 250 m resolution. Guo *et al.* (2019) demonstrated that the accuracy of SOC prediction is inversely correlated to spatial resolution. Similarly, Garosi *et al.* (2022) used variable resolutions from 2 m to 30 m to test model accuracy and showed that 10 m pixel-size Sentinel-2 images combined with the topographic attributes of digital elevation models produced the best SOC prediction. Both studies identified pixel size or spatial resolution as an important variable affecting model accuracy and SOC estimation. This suggests that the community must proceed with a better resolution for example 10—12 m.

Spectral resolution describes a sensor's capacity to differentiate between fine distinctions in wavelengths. Multispectral sensors have three to ten bands, while hyperspectral sensors have hundreds of them. Castaldi *et al.* (2016) found that the benefit of higher spectral resolution can be partially offset by the amplification of noise when increasing the number of spectral bands. A complex combination of topography, soil type, climate and biological processes leads to high SOC variability in time and space, so capturing spatiotemporally continuous images is important (Angelopoulou *et al.*, 2019).

Remote sensing has evolved from multi- to hyperspectral data. Since the early 2000s, hyperspectral images have been made available by the Hyperion sensor and the Compact High-Resolution Imaging Spectrometer (CHRIS), with 17 m resolution under the Project for On-Board Autonomy (PROBA-1) microsatellite. Since 2019, the PRecursore IperSpettrale della Missione Applicativa (PRISMA) has delivered hundreds of datapoints to the community. There are others in operation, such as the Environmental Mapping and Analysis Programme (EnMAP) and the Earth Surface Mineral Dust Source Investigation (EMIT), along with other, upcoming Landsat-hyperspectral data. In conclusion, the remote sensing community is moving towards the hyperspectral EO model. This will make it possible to detect very similar bands of soil properties to the laboratory.

9.1.5 A GLOBAL SPATIALIZATION OF SOIL ORGANIC CARBON AND SOIL PROPERTIES

Alterations in land use and vegetation patterns, as visible by seven EO systems, can be used to calculate net primary productivity and SOC sequestration potential (Miller and Michalak, 2020). Satellite imagery can also be used as a covariate in digital soil mapping, where soil properties and satellite information are used to predict the SOC at various depths correlating with ground point observations (Maynard and Levi, 2017). A combination of remote and in situ point data will be critical in predicting or creating high-resolution and accurate SOC maps. A model derived from point-source measurement of SOC and correlated with spectral reflectance on remotely sensed imagery can provide complete datasets for extrapolating or estimating SOC in unsampled locations for spatial continuity. The high temporal and spatial resolution of remote imagery offers an unprecedented possibility to study and monitor SOC change over space—time dynamics, reflecting vegetation change, climate change and land use. van Wesemael *et al.* (2022) indicate several strategic advantages of and limitations on the carbon quantification of remote sensing and conclude that hyperspectral data can detect carbon.

Three dominant approaches to SOC quantification have emerged: remote sensing, periodic soil sampling and process-based modelling. While remote sensing offers scalability for monitoring, reporting and verifying SOC, its broad implementation necessitates further research and specialized expertise. Advanced remote sensing tools can monitor key agricultural metrics, such as crop yields and the adoption of conservation techniques, such as no-till farming and cover cropping. These metrics can then inform process-based models to ensure precise SOC change estimations at farm level. Consequently, this data-driven approach can tailor incentives or rewards for farmers based on SOC: measurement and monitoring using remote-sensing-data-verifiable practices. Innovative tools, such as the Operational Tillage Information System (OpTIS) and Descartes Labs products for carbon monitoring, exemplify this trend. Drawing on data from multiple earth-observing satellites, these tools map farmland conditions annually to monitor vital indicators such as cover-crop growth, crop residues and tillage practices (Kubitza *et al.*, 2020).

9.1.6 UPSCALING DETECTION OF AGRICULTURAL PRACTICES

The geospatial and temporal variability of the impact of specific practices, such as cover cropping or no-till, pose challenges for the scalable quantification of emissions reduction and the deployment of incentives to drive increased adoption (Brummitt *et al.*, 2024). Demattê *et al.* (2020) developed a global pipeline using temporal satellite data that detects a proxy that can provide important clues as to the type of land management being used (tillage or no-tillage). The technique enables the retrieval of bare surfaces on 32 percent of the Earth's total land area and on 95 percent of land when considering only agricultural areas in the last 30 years. From a multitemporal perspective, the technique found a 2.8 percent increase in bare surfaces during the 30-year period on a global scale. However, the rate of soil exposure decreased by about 4.8 percent over the same 30-year period. The increase in bare surfaces shows that agricultural areas are increasing worldwide. The decreasing rate indicates that, contrary to popular opinion, more soils have been covered due to the adoption of conservation agriculture practices, which may reduce soil degradation. In conclusion, this is a promising tool to help upscale information, as indicated by Brummitt *et al.* (2024).

9.1.7 RESEARCH GAPS

Surface temperature is an important topic, as it influences plant growth, microbiological activities and carbon dynamics. Land surface temperature measures how hot the Earth's surface feels at a specific location. These techniques also assist with hydrological dynamics (Allies *et al.*, 2020). Remote sensing can capture this information in specific thermal spectral regions. However, there is a deficiency in existing remote sensing technologies operating at the necessary thermal infrared wavelengths. Missions such as Sentinel-3 and the Moderate Resolution Imaging Spectroradiometer (MODIS) can provide data at a high temporal resolution, but at insufficient spatial resolution. Conversely, missions offering higher spatial resolution, such as the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) at 70 m and Landsat 9 at 100 m, are rare due to the short return interval of satellites in many areas and continuous frequency being unavailable. They are, therefore, unsuitable for regular monitoring. Consequently, there are currently few plant-temperature sensing solution available that can deliver the necessary blend of timely, precise and field-scale measurements required for effective smart water management. Three main missions are currently in preparation: The French/Indian Thermal InfraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA) mission, the NASA Surface Biology and Geology mission, and the European Space Agency/Copernicus Land Surface Temperature Mission (LSTM). TRISHNA will be able to acquire imagery of each place on Earth within three days (with different viewing angles) or eight days (with the same acquisition angle), with a spatial resolution of 57 m (land) and 1 km (ocean). The satellite combines two instruments to cover the visible near infrared (VNIR)/short-wave infrared (SWIR) spectral range (six bands) and the long-wave infrared (LWIR) range (four bands). The launch is scheduled for 2025.

The NASA Jet Propulsion Laboratory Surface Biology and Geology mission is scheduled for 2028. It combines a hyperspectral imaging spectrometer (visible short-wave infrared at about 30 m pixel resolution) with multispectral instruments covering mid-wave infrared and LWIR (about 60 m pixel resolution). The temporal resolution is planned to be less than or equal to three days.

The European Space Agency/Copernicus LSTM will operate in the VNIR/SWIR and LWIR spectral ranges. The spatial resolution of 50 m and a 1–3-day revisit with high accuracy will produce a very good database for the regular monitoring of environmental and agricultural conditions. The LSTM will comprise a pair of similar instruments with expected launch dates in 2028 (LSTM-A) and 2030 (LSTM-B). The mission with the highest potential to act as a precursor to public missions is the High-Precision Versatile Ecosphere Monitoring (HiVE) mission. HiVE is a pioneering microsatellite constellation designed explicitly for high-resolution thermal infrared land surface temperature monitoring (Taymans *et al.*, 2023). Constellr, a tech company using EO for agronomy, collaborates with industry leaders such as OHB System, NanoAvionics and Fraunhofer EMI, bringing together innovative approaches from both the emerging new space sector and traditional space programmes.

The primary objective of the HiVE mission is to generate and deliver global-coverage land surface temperature imagery, optimized specifically for applications in water and sustainable resource management, agricultural monitoring and temperature-based crop health management.

9.1.8 CONCLUSION

- Efforts are needed in terms of human and commercial resources using proximal sensors to realise SOC analysis.
- It is worth pushing satellite companies to insert/create new hyperspectral on-board sensors in with more bands in the thermal region.
- Efforts are needed to create an integrated centre of world data to reduce the need for new data.
- Efforts are needed to increase training in soil sensing, as it is a powerful technique with multiple applications in several disciplines, and to take advantage of opportunities to harness AI.
- The remote sensing community must drive efforts to produce soil information based on new co-variables, as soils are increasingly going to be covered.
- Mapping SOC under better spatial resolution is crucial (12 m or better).
- Techniques to determine subsurface carbon properties need to be used, and soil sensing can assist.

9.2. ARTIFICIAL INTELLIGENCE IN AGRICULTURAL SYSTEMS

9.2.1 WHAT HAVE WE LEARNED FROM INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE REPORTS?

The IPCC recognizes the transformative potential of technological advancements, including digital tools and data-driven solutions, in addressing agricultural challenges. While AI is not explicitly detailed, its applications align with the report's emphasis on precision agriculture, real-time monitoring and scenario analysis. These innovations enable farmers to make informed decisions, optimize resource use and enhance the resilience of agricultural systems to climate variability (Mbow *et al.*, 2019; Bezner Kerr *et al.*, 2022; IPCC, 2022).

9.2.2 ARTIFICIAL INTELLIGENCE AND CLIMATE-SMART AGRICULTURE

Climate-smart agriculture

CSA is an integrative approach designed to achieve three interconnected goals: sustainably increasing productivity, enhancing resilience and reducing GHG emissions from agriculture (Azadi *et al.*, 2021; Wakweya, 2023; Vishnoi and Goel, 2024). The CSA approach aligns with the objectives outlined in Working Group III's contribution to the IPCC's Sixth Assessment Report, which emphasizes addressing food security challenges posed by climate change, particularly in regions prone to droughts, floods and extreme temperatures (IPCC, 2022). While CSA is not explicitly mentioned in the report, its principles resonate with the IPCC's focus on promoting sustainable agricultural practices, enhancing resilience and reducing GHG emissions (Mbow *et al.*, 2019; Bezner Kerr *et al.*, 2022; IPCC, 2022).

To increase crop yield, CSA draws on innovative practices such as conservation tillage, crop diversification, precision nutrient management and efficient irrigation systems. These approaches could be enhanced by AI technologies, which analyse complex datasets to provide actionable insights for optimizing inputs such as water and fertilizers (Imade *et al.*, 2024). For resilience, CSA incorporates practices that enhance soil health, biodiversity and adaptive capacity, such as agroforestry and the use of climate-resilient crop varieties. AI-driven predictive models may help anticipate climate impacts, enabling farmers to make informed decisions about planting and harvesting schedules (Shaikh, Rasool and Lone, 2022; Kumari *et al.*, 2023). Similarly, AI-informed models can improve the quantification of soil carbon stock dynamics as a function of management, climate and edaphic conditions, as a key indicator of soil health (Liu *et al.*, 2024).

Reducing emissions is a critical goal of CSA, so strategies include adopting low-emission livestock practices, managing CH_4 emissions from rice paddies, improving nitrogen-use efficiency in fertilizers and increasing carbon stocks in soil. AI-powered monitoring systems could play a pivotal role in quantifying and reducing emissions, providing real-time data to assess the effectiveness of mitigation practices (Shaikh, Rasool and Lone, 2022; Saberi Kamarposhti *et al.*, 2024).

Integration of artificial intelligence into agricultural practices

AI may be transforming agricultural systems through advanced data-driven decision-making, optimizing resource utilization and enhancing climate resilience in farming practices (Indu, Nanjundan and Thomas, 2024). Through the analysis of historical and real-time data, machine learning models identify trends and vulnerabilities in farming systems, providing precise recommendations on irrigation, pest control and fertilization (McCampbell *et al.*, 2023). AI also facilitates the development of decision support systems, which integrate multiple layers of information to guide land-use planning and farm management under various climate scenarios (Kalyanaraman *et al.*, 2022).

For instance, predictive analytics powered by AI can simulate the impacts of different management practices on crop yields and environmental outcomes. These simulations help policymakers and farmers evaluate trade-offs and identify optimal strategies for achieving both productivity and sustainability goals. Moreover, AI technologies enhance precision agriculture by integrating remote sensing data, drone imagery and Internet of Things devices, allowing for targeted interventions that minimize waste and environmental impact (Benos *et al.*, 2021).

Process-based crop models

Process-based crop models (PBCMs) simulate the growth and development of crops by incorporating biophysical and physiological processes. These models are invaluable in exploring the impacts of climate change on agricultural systems, as they quantify relationships between variables such as temperature, precipitation and crop yields (Bezner Kerr *et al.*, 2022).

PBCMs — such as the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom *et al.*, 2019), the Agricultural Production Systems Simulator (APSIM) (Keating *et al.*, 2003) and the World Food Studies Simulator (WOFOST) (De Wit *et al.*, 2019) — are widely used to simulate various management scenarios, including soil carbon sequestration, nitrogen cycling, WUE and crop yield, under different environmental and climate change conditions, and predict the impact of agricultural management practices on environmental resource use and crop yield (Marin *et al.*, 2023; Kim *et al.*, 2024). They ensure a deeper understanding of how to maintain agricultural outputs while securing food security and minimizing environmental impacts (Figueiredo Moura da Silva *et al.*, 2024, 2025). In addition, the Agricultural Model Intercomparison and Improvement Project fosters collaboration between these modelling frameworks to assess and enhance their performance under climate change scenarios, ensuring a comprehensive understanding of global agricultural systems (Rosenzweig *et al.*, 2021; Kothari *et al.*, 2022).

The integration of AI with PBCMs should provide significant opportunities to enhance their predictive accuracy and scalability. By leveraging machine learning techniques such as neural networks and random forests, these models can effectively analyse extensive datasets, improving calibration and identifying key parameters critical for accurate simulations (Elavarasan and Vincent, 2021; Fan *et al.*, 2021). Furthermore, AI combined with PBCMs has the potential to facilitate real-time scenario analysis, allowing stakeholders to evaluate the impacts of various adaptation and mitigation strategies under diverse climate conditions. These capabilities also support the development of digital tools in agriculture, a concept emphasized in the contribution of Working Group II to the Sixth IPCC Assessment Report, which highlights the role of such tools in advancing climate adaptation strategies, optimizing resource use, and improving agricultural resilience (Bezner Kerr *et al.*, 2022).

Artificial intelligence and greenhouse gas mitigation in agriculture

Sources and sinks of GHGs from agricultural soils are challenging to quantify due to their high spatial and temporal variability and the many complex biogeochemical and management-related controls involved (Paustian *et al.*, 2016). High-quality quantification methods, applicable from landscape to national scale, are essential to designing effective mitigation strategies. Dynamic process-based biogeochemical models, together with ground-observation networks, are the current state-of-the-art tools for quantifying GHG emissions (Smith *et al.*, 2020). However, limited process understanding, the high spatiotemporal variability of process-driving variables and sparse in situ measurements contribute to high levels of uncertainty with current quantification systems (Liu *et al.*, 2022). AI methods, such as knowledge-guided machine learning, constitute a hybrid approach with process-based modelling (Liu *et al.*, 2024). They can make use of observation data from in situ measurement networks, as well as "big data" from remote sensing of vegetation dynamics (for example, photosynthesis, leaf area and biomass), that can reduce uncertainty and facilitate high-resolution measurement and monitoring of soil GHG emissions and net CO_2 uptake (Yang *et al.*, 2023). For decision support and policy assessment, AI-enabled model surrogates facilitate multicriteria optimization methods that can guide the selection of alternative incentive structures (Nguyen, Nong and Paustian, 2019).

Geotechnologies and artificial intelligence in agriculture

Geotechnologies, such as GIS, remote sensing and global positioning systems (GPS), are essential tools in modern agriculture. When integrated with AI, these technologies provide comprehensive insights into spatial and temporal variations in agricultural systems (Kim *et al.*, 2021).

AI-powered remote sensing, for instance, processes satellite imagery to monitor crop health, soil moisture and pest infestations (Mmbando, 2025). Such insights enable farmers to implement targeted interventions, reducing input costs and environmental impact. GIS platforms, combined with AI, facilitate precision agriculture by mapping field variability and optimizing input applications (Sharma and Shivandu, 2024). Furthermore, GPS-guided machinery ensures accurate planting, fertilizing and harvesting, enhancing efficiency and minimizing resource waste (Getahun, Kefale and Gelaye, 2024).

Robotics and mechanization in agriculture

Robotics and mechanization are revolutionizing agriculture by integrating advanced AI technologies into farm operations (Sharma and Shivandu, 2024). Autonomous vehicles, robotic harvesters and precision seeding systems are examples of innovations that enhance efficiency and reduce labour costs (Padhiary, Kumar and Sethi, 2024). These technologies are equipped with AI-powered sensors and decision-making algorithms that optimize tasks such as planting, weeding and harvesting based on real-time data (Mishra and Mishra, 2024).

For example, autonomous tractors use AI to navigate fields, adjust operations based on soil conditions and minimize fuel consumption (Padhiary, Kumar and Sethi, 2024). Similarly, robotic systems for harvesting high-value crops, such as fruits and vegetables, employ computer vision and machine learning to identify ripeness and reduce waste (Tian *et al.*, 2020). These advancements not only improve crop yield, but also reduce the environmental footprint of agriculture by optimizing resource use and minimizing emissions.

9.2.3 CHALLENGES AND OPPORTUNITIES

Data gaps

The lack of standardized, high-quality datasets remains a significant barrier to AI adoption in agriculture. Agricultural systems are inherently complex, with interactions between climatic, biological and management factors requiring extensive datasets for accurate modelling and decision-making (Jones *et al.*, 2017). Expanding open data initiatives and investing in comprehensive data infrastructure is critical to overcoming this challenge (Attard *et al.*, 2015; Kebede *et al.*, 2024). Regional and global monitoring initiatives, such as the NASA Prediction Of Worldwide Energy Resources project and the Copernicus programme, provide valuable data resources to support AI-driven agricultural solutions (Garcia-del-Real and Alcaráz, 2024).

Ethical considerations

AI deployment must prioritize equity, ensuring that smallholder farmers and marginalized communities benefit from technological advancements. The inherent risks of data privacy issues, algorithmic bias and uneven access to technology disproportionately affect these communities (Jamba and Marambi, 2024). Furthermore, co-designing AI solutions with local stakeholders ensures that innovations are culturally relevant and address the specific challenges faced by diverse farming systems (Ndege, Marshall and Byrne, 2024).

Technical barriers

Infrastructural limitations, such as inadequate internet connectivity and high computational costs, continue to hinder AI adoption, especially in low-income regions (Khan, Umer and Faruqe, 2024). Innovations in cloud computing, edge computing and low-cost AI frameworks are critical to bridging this gap (Nain, Pattanaik and Sharma, 2022). Training and capacity-building programmes, tailored to the local contexts, are equally vital in ensuring that farmers and agricultural professionals can effectively leverage AI tools (Bampasidou *et al.*, 2024).

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10. Food systems — mitigation, impacts and adaptation

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10.1. UPDATE ON GLOBAL AGRICULTURE AND FOOD SYSTEMS STATUS SINCE 2019

Agrifood systems emissions are generated within the farm gate (from crop and livestock production), by land-use change (from deforestation, biomass fires and peatland degradation linked to agricultural land expansion) and in pre- and post-production processes (from activities across the food supply chain, including processing, retail, household consumption and the disposal of food waste) (FAO, 2024; IPCC, 2019a).

Activity data, emissions estimates and emissions indicators, such as agrifood shares of total emissions, agrifood emissions per capita and emissions intensities of different food commodities, are produced at regular intervals by the European Union Joint Research Centre (Crippa *et al.*, 2021, 2022) and FAO (FAO, 2024; Tubiello *et al.*, 2022). These data, available at the national level, facilitate country analysis in support of national inventory reporting and related submissions. They have recently been incorporated into a number of sustainability metrics for agriculture, including the Food Systems Countdown Initiative (Schneider *et al.*, 2023) and SDG Indicator 2.4.1 on productive and sustainable agriculture (FAO, 2024).

Agrifood systems account for a substantial proportion of global anthropogenic GHG emissions (Mbow *et al.*, 2019). Recent country-level estimates suggest that agrifood systems currently generate 16–18 $GtCO_2e$ annually, or about 30 percent of total GHG emissions (Crippa *et al.*, 2022; Tubiello *et al.*, 2022). The IPCC's Sixth Assessment Report presented a wider range of 23–42 percent, underscoring significant uncertainty due to incomplete knowledge and the adoption of widely different methodological approaches (Babiker *et al.*, 2022).

In individual GHG terms, agrifood systems generate about 20 percent of total anthropogenic CO_2 emissions, primarily from land-use change, on-farm energy use and energy consumption in food supply chains and households. They are also responsible for 50 percent of all anthropogenic CH_4 emissions, largely from enteric fermentation from ruminant livestock and solid food waste disposal, as well as nearly 80 percent of global N_2O emissions, mainly from fertilizer application and manure management. Agrifood system cold chains, primarily in food retail and households, are further estimated to account for 30 percent of global fluorinated gas emissions (FAO, 2024; Crippa *et al.*, 2024; Flammini *et al.*, 2024).

Despite the magnitude and diversity of GHG emissions from agrifood systems, there are no internationally coordinated initiatives within the scientific community aimed at standardizing system boundaries, harmonizing methodological approaches, and formulating transparent protocols for quantifying GHG emissions and removals across all agrifood system activities. This gap can lead to divergent assessments of where to target mitigation interventions, as well as confusion about how to assess their efficacy and monitor their impact over time in line with stated net-zero goals (Crippa *et al.*, 2022). Karl *et al.* (2024) recently suggested that an internationally coordinated process should advance scientific consensus in four key areas: i) definitions of agrifood systems emissions boundaries and nomenclature; ii) protocols to allocate broader sectoral emissions to agrifood systems; iii) prioritization of critical research areas to enhance activity data and emissions factors; and iv) the development of a balanced framework for estimating and monitoring the impact of mitigation interventions in light of other agrifood systems imperatives.

10.2. DEMAND-SIDE CLIMATE ACTIONS IN FOOD SYSTEMS

This section delves into the crucial role of demand-side mitigation options in achieving sustainable food systems, focusing on the interconnectedness between consumer behaviour, policy interventions and technological advancements. Building on the IPCC (2019a) Special Report on Climate Change and Land, this section identifies new areas of research and existing knowledge gaps that require attention from policymakers to develop innovative and inclusive solutions. The literature suggests that shifting to an alternative diet with less red meat and reducing food waste at the consumer end have high potential to reduce GHG emissions (IPCC, 2022). Recent studies explore: i) whether such solutions are cost saving, ii) which interventions can help to change consumer behaviour, how these interventions can be implemented and by whom, and iii) whether existing policies support these behavioural change interventions. This section discusses these three topics in terms of the following two key demand-side solutions: i) a shift to balanced, sustainable healthy diets meeting nutritional needs and ii) the reduction of food waste at the consumer end (IPCC, 2022).

10.2.1 SHIFTING TO BALANCED, SUSTAINABLE HEALTHY DIETS TO MEET NUTRITIONAL NEEDS

The IPCC (2022, p33) defines sustainable healthy diets as diets that "promote all dimensions of an individual's' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described by FAO and WHO."

The literature suggests that predominantly plant-based diets, consuming locally produced food, have substantially lower environmental impacts, with fewer GHG emissions, less land and water use, and less nutrient pollution than diets rich in animal products, particularly red meat and processed food (IPCC, 2022; Schanes, Dobernig and Gözet, 2018; Bajželj *et al.*, 2014). Insects also present a promising alternative protein source, with lower emissions and resource requirements (Orkusz *et al.*, 2020).

Key research findings and gaps

Cost savings

The cost aspects of dietary shifts towards balanced, sustainable healthy diets meeting nutritional needs have rarely been assessed. The few studies that do exist conclude that shifting to such diets may not always be cost saving and vary significantly with the geographical location of the study. For example, in rural India, the shift towards the EAT–Lancet diet was estimated to be 3—5 times more expensive than current diets (Gupta *et al.*, 2021). In the past, a similar result was found for rural areas of South Africa, where shifting to national dietary guidelines would be 2—3 times more expensive than the actual diet (Temple *et al.*, 2011). While past studies exploring the cost changes of shifting to vegetarian/vegan alternatives from current diets in certain countries have reported cost savings (Grabs, 2015; Berners-Lee *et al.*, 2012), some recent studies on shifting to vegetarian/vegan/flexitarian/pescetarian diets have reported cost increases, but for a different set of countries (Pais, Marques and Fuinhas, 2022; de Pee *et al.*, 2021; Arrieta *et al.*, 2022). To aid policymakers in developing innovative and inclusive solutions, more country-specific evidence is needed to clearly understand the factors influencing cost savings in dietary shifts. What is more, evidence to date is based mainly on scenario analysis rather than real-world implementation. Further research is needed to understand both the direct out-of-pocket costs and indirect costs and benefits (such as health benefits) of shifting to balanced, sustainable and healthy diets.

Interventions to help change consumer behaviour, implementation and social actors

Many studies are exploring the plethora of interventions available to aid in changing consumer behaviour, including choice architecture and nudging (Some *et al.*, 2022). Studies demonstrate the effectiveness of various policy interventions in promoting sustainable food consumption and information campaigns to raise consumer awareness. For example, taxes on sugary drinks have been shown to reduce consumption and generate revenue for health programmes (Liu *et al.*, 2022). While the effectiveness of these interventions is being assessed, there is still a lack of evidence on their long-term impact on human behaviour and effectiveness in diverse cultural contexts. This includes understanding the acceptability of alternative protein sources, such as edible insects (Orkusz *et al.*, 2020) and plant-based burgers (Petrat-Melin and Dam, 2023) and identifying barriers to the adoption of alternative diets in different cultural contexts. Behavioural research highlights the influence of social norms, cultural preferences and economic factors on food choices (Enriquez and Archila-Godinez, 2022; Banerjee and John, 2021). Therefore, understanding the drivers of food choices can help design effective interventions (Rehman, Edkins and Ogrinc, 2024; Nguyen *et al.*, 2021).

Recent studies recognize that successful implementation of behavioural interventions relies on collaboration between various social actors, from governments, the food industry and civil society to researchers and individuals (Some *et al.*, 2022). However, gaps remain in terms of real-world implementation. There are also research gaps when it comes to context-specific evidence, the long-term impacts of nudging, and the acceptability and perception of alternative proteins, such as edible insects, in different cultural contexts. Research is also needed to understand the influence of marketing and media on choices made by consumers. Addressing these gaps is crucial to understanding what can work in terms of changing consumer behaviour towards adopting balanced, sustainable, healthy diets that meet their nutritional needs.

In the context of technological advancement, cellular agriculture offers a novel approach to producing animal-sourced foods without the environmental and ethical concerns associated with traditional livestock farming (Rønning, Pedersen and Bjørnerud, 2024; Jahir *et al.*, 2023). Preliminary assessments suggest that cellular agriculture has the potential to significantly reduce the environmental impacts of meat production, particularly GHG emissions and land use, though it increases demand for critical materials (El Wali *et al.*, 2024). Therefore, further research is needed to understand its overall impact. Moreover, large-scale facilities (that have economies of scale) with the potential to produce cell-cultured meat at a cost comparable to traditional slaughterhouses need to be widely explored (Treich, 2021). Garrison, Biermacher and Brorsen (2022) estimate the wholesale cost of cell-cultured meat in a large-scale facility to be USD 63/kg. Studies are ongoing to optimize cell culture techniques, reduce production costs and improve the quality of cell-based products (Jahir *et al.*, 2023). Studies are also exploring consumer acceptance of cellular agricultural products and identifying potential barriers to market adoption, such as neophobia (fear of new things) and concerns about safety and "naturalness" (Moritz, Tuomisto and Ryynänen, 2022; Bryant and Barnett, 2020). Understanding consumer perception is crucial to the successful commercialization of cellular agriculture products. Research is also needed to understand the regulatory challenges involved, such as guidelines and standards for cultured meat production, labelling and safety. Research should focus on integrating cellular agriculture into existing food systems (models) to understand potential impacts on livestock farmers and rural economies to ensure a just transition.

The role of existing policies in supporting behavioural change

While various interventions show positive results in shifting consumer behaviour, there remains a critical gap in policy support (Dogbe *et al.*, 2024; Nguyen *et al.*, 2021). Many studies highlight the potential of information campaigns and nudging strategies (Blackford, 2021), but few examine whether existing policies such as taxes, subsidies and education campaigns influence dietary shifts. This gap hinders large-scale implementation and raises questions about the long-term effectiveness of behavioural interventions. Further research is needed to assess the policy landscape and identify opportunities to align policies with the promotion of sustainable and healthy diets. This includes investigating how policies such as food labelling regulations, dietary guidelines and public procurement policies can incentivize sustainable practices in the food industry, support consumer education and address potential barriers to accessing affordable and nutritional plant-based options and alternative diets. Research is needed to understand and establish regulatory frameworks and safety standards for meat alternatives (such as insects and plant-based protein) (Treich, 2021; Baiano, 2020). This will ensure consumer confidence and facilitate market access for alternative diets.

10.2.2 FOOD WASTE

The recent UNEP (2024) Food Waste Index Report highlights that 1.05 Gt of food is wasted globally, of which households are responsible for 631 Mt. Food waste reduction at the consumer level is a key demand-side solution that not only reduces environmental pressure (indirectly reducing resource waste), but also GHG emissions associated with food production (UNEP, 2024).

This section examines the current state of research on consumer-level food waste reduction, focusing on cost implications, interventions and policy support, while highlighting key knowledge gaps.

Key research findings and gaps

Cost savings

While the environmental benefits of reducing food waste are widely recognized, the economic aspects, particularly at consumer level, are less explored. Studies highlight cost savings as a significant motivator for consumers to reduce food waste (Goodman-Smith, Mirosa and Mirosa, 2020; de Visser-Amundson and Kleijnen, 2020). However, research quantifying the economic benefits of various food waste reduction strategies is limited. Conrad (2020) shows that reducing food waste in the United States could reduce 27 percent of expenditure on food. Recent studies also examine the cost effectiveness of food waste interventions. Read and Muth (2021) reported that USD 126 million to USD 595 million would be needed annually in the United States to implement nationwide food waste interventions, such as consumer education and public awareness campaigns, spoilage prevention packaging for produce and meat, standardization of date labels, and foodservice waste-tracking systems. Studies often focus on the cost of food waste at the national or global level (von Massow *et al.*, 2019; Conrad, 2020), but detailed analyses of cost savings for individual households are lacking. Further research is needed to understand how different interventions, such as meal planning, storage practices and utilizing leftovers, translate into actual cost savings for consumers across diverse income levels and cultural contexts. In addition, research on the cost effectiveness of food waste reduction interventions is mostly based on scenario analysis and not real-world implementation. Therefore, future studies could investigate how different food waste reduction interventions implemented in different contexts lead to cost savings for consumers. This will aid in developing innovative and inclusive policies and upscale the real-world implementation of food waste reduction interventions.

Interventions aiding in changing consumer behaviour, implementation and social actors

Recent studies have explored interventions that aid in the reduction of food waste at the consumer end (Some *et al*., 2022; Lorenz-Walther *et al*., 2019). Reynolds *et al*. (2019), for instance, demonstrated that a 19 percent reduction in food waste occurred when a Norwegian hotel reduced plate size. Researchers, for a long time now, have been conducting studies to understand consumer behaviour, evaluating the effectiveness of interventions and developing innovative solutions to promote food waste reduction (Lorenz-Walther *et al*., 2019). This extensive research has led to greater use of posters and infographics in institutional canteens to encourage food waste reduction. However, there is still a lack of evidence on the long-term impact and effectiveness of such soft nudges in diverse cultural contexts. Some *et al*. (2022) emphasizes the importance of various social actors in implementing food waste reduction interventions, listing 21 interventions that various social actors can adopt to reduce food waste. Individuals play a crucial role here by practising sustainable behaviour, such as reducing portion sizes and using leftovers (Attiq *et al*., 2021; Talwar *et al*., 2021). Despite the growing body of research on identifying interventions and understanding the effectiveness of a handful of them, gaps remain in understanding their long-term impact on behavioural change and their effectiveness in diverse cultural contexts. More research is needed on the real-world implementation of these interventions, considering factors such as cost effectiveness, accessibility and cultural appropriateness.

Role of existing policies in supporting behavioural change

Various governments (for example, in the European Union, India and China) are introducing regulations that can incentivize sustainable practices in the food industry, support consumer education on food waste reduction, and invest in infrastructure for composting and food waste recycling (European Commission, 2024; Government of India, 2022; Sheldon, 2021). These regulations, which include imposing fines on restaurants with excessive leftovers and reconsidering extravagant buffets at ceremonies, aim to influence consumer choice and promote sustainable food consumption. Research has shown that price instruments, such as fees and taxes, are less effective when it comes to food waste reduction (Schanes, Dobernig and Gözet, 2018), suggesting that other policy approaches may be more effective in driving behavioural change. Further research is needed to assess the policy landscape and identify opportunities to align policies with the promotion of food waste reduction. This includes integrating food waste considerations into various policy areas, such as dietary guidelines, public procurement policies and educational curricula, and developing comprehensive policy frameworks that incentivize sustainable practices throughout the food supply chain, from farm to fork (see, for example, European Commission, 2020). Research gaps also exist in understanding the barriers to implementing innovative solutions such as community fridges. Also, more research is needed to understand the infrastructural support required to reduce food waste in different country contexts, as food texture, culinary traditions and typical meal composition vary widely from country to country.

10.3. FOOD SYSTEMS — SYSTEMIC APPROACHES

10.3.1 AGROECOLOGY

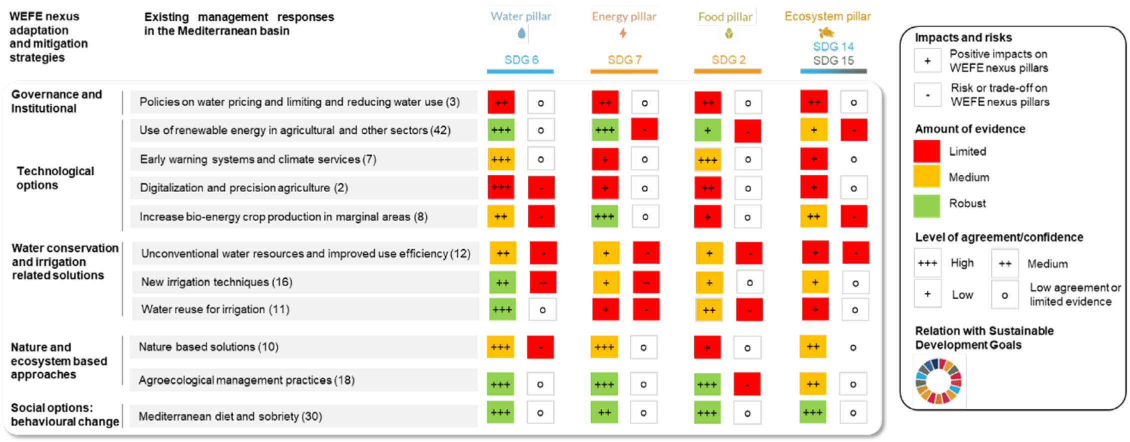
Given the current state of climate emergency and the profound transformations required to deal with food systems-associated challenges, new research efforts need to focus on tackling the issue from a systems perspective. Isolated actions and strategies will not result in satisfactory outcomes to address challenges in time. Consequently, systemic approaches that analyse actions while considering both mitigation and adaptation, as well as synergies and trade-offs with other SDGs, are becoming more relevant. A systemic approach to food systems in the context of climate change can identify those actions which, in combination, show the highest mitigation and adaptation potential. In addition, social dimensions need to be considered. The 2022 IPCC Working Group III report strongly recommends climate-resilient development pathways that tackle equity dimensions as essential to increasing the efficiency of climate action (IPCC, 2022). In food systems, this translates into agroecology and nexus approaches. FAO (2019) states that apart from optimizing the interactions between plants, animals, humans and the environment, agroecology seeks to transform food and agricultural systems, addressing the root causes of problems in an integrated way and providing holistic and long-term solutions. This includes an explicit consideration of the social and economic dimensions of food systems, placing a strong focus on rights. The focus on rights is also promoted by the IPCC (2022) report as an effective approach to climate change mitigation and adaptation.

Agroecology, defined as the ecological design of food systems, is an efficient, systemic approach to favour changes in food systems that contribute to both mitigation and adaptation of climate change, as well as increasing biodiversity and socioeconomic resilience (Bezner Kerr *et al.*, 2023). Some of the practices assessed in Sections 3-6 (agroforestry, mixed crop—livestock systems, reduced tillage, cover crops, mulching and so on) that not only have strong mitigation potential, but also adaptation potential, are included within the diversity of agroecological practices (IPCC, 2022; HLPE, 2019). In many cases, these actions also contribute to the achievement of SDG 5, SDG 12, SDG 14 or SDG 15. Also, agroecology is based on bottom-up and territorial processes, building on the co-creation of knowledge, combining science with the traditional, practical and local knowledge of producers. By enhancing autonomy and adaptive capacity, agroecology empowers producers and communities to act as key agents of change (FAO, 2019).

10.3.2 NEXUS

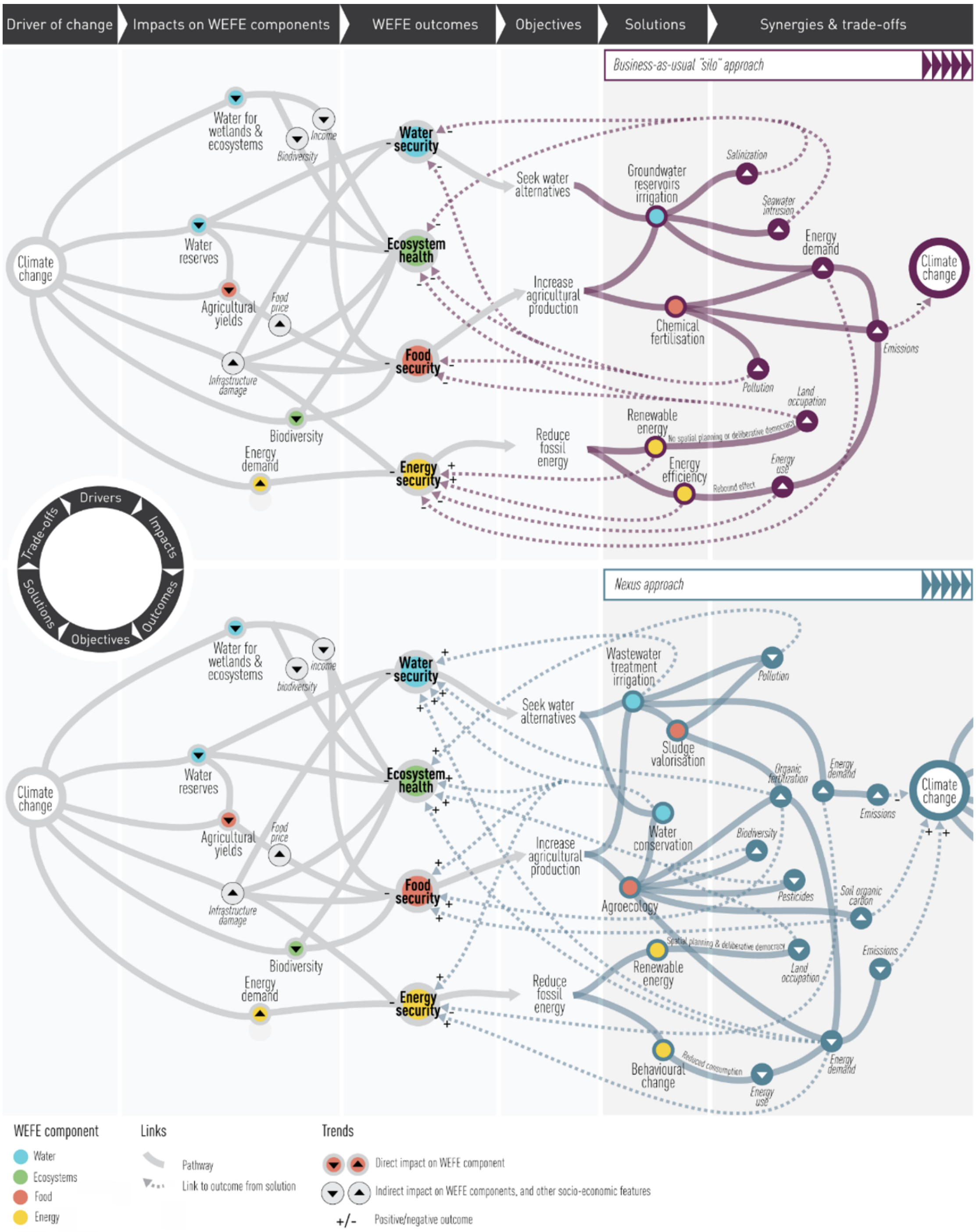
Food systems can also be analysed from a nexus perspective to evaluate the synergies, trade-offs, cascading effects, interactions and multiple feedback loops occurring within one given system as a result of a given action. Nexus approaches are developed to assess integrated approaches in connection with SDGs. The 2024 nexus report of the Mediterranean Experts on Climate and Environmental Change evaluated several actions in food systems in the Mediterranean region, showing that socioecological innovations and behavioural changes — particularly agroecology and behavioural changes towards sobriety (including a reduction of animal products in the region) — provided the greatest efficiency in terms of synergies among different objectives (mitigation, adaptation) and fulfilment of a variety of SDGs (see **Figures 10.1** and **10.2**) (MedECC, 2024). In line with these results, Röös *et al.* (2022) estimated that a systemic approach that combines a diversity of actions (agroecological practices in combination with healthy diets) could help to substantially reduce emissions in Europe while meeting other environmental targets.

FIGURE 10.1. Assessment of the main impacts and trade-offs of the water–energy–food–ecosystems nexus adaptation and mitigation solutions implemented in the Mediterranean countries



Source: MedECC. 2024. *Interlinking climate change with the Water-Energy-Food-Ecosystems (WEFE) nexus in the Mediterranean Basin.* Marseille, France. https://www.medecc.org/medecc-reports/climate-wefe-nexus

FIGURE 10.2. Impacts, interactions and cascading effects on the water—energy—food—ecosystem outcomes of drivers of change and solutions



Source: MedECC. 2024. *Interlinking climate change with the Water-Energy-Food-Ecosystems (WEFE) nexus in the Mediterranean Basin.* Marseille, France. https://www.medecc.org/medecc-reports/climate-wefe-nexus

10.3.3 TELECOUPLING

Telecoupling is a strategy that comprehensively analyses the socioeconomic and environmental impacts of particular activities or sectors over long distances, helping to generate information on coupled human and natural systems. The framework provides analytical tools to explain and understand the feedbacks between distant systems and subsystems in an increasingly globalized world (De Castro, De Lima and Romano, 2022). The telecoupling impacts of food systems have been reported in recent years, making a relevant contribution to the climate change debate, including use in national inventories of GHG emissions.

The IPCC (2019) Special Report on Climate Change and Land reported emissions from food systems for the first time. This was a first big step in understanding actual food-system contributions to emissions, beyond those estimated using the classical AFOLU approach used in national inventories. The driving forces behind the production and consumption of food are relevant to this debate. For instance, high levels of meat intake in affluent countries are leading to GHG emissions in Brazil, Argentina and other countries specialized in feed (such as soy) and animal products. Sylvester *et al.* (2024) found that trade- and demand-side dynamics, namely foreign direct investment and urban population growth, have played important roles in influencing deforestation trends at the global, Asian and Latin American scales (during the period 2004 and 2021), suggesting that food system-based interventions could be effective in reducing deforestation in these regions. Galvan-Miyoshi *et al.* (2022) analysed the North American Free Trade Agreement and its impacts on land use and GHG emissions, particularly those associated with beef production, and found that the intensification of Mexican beef production did not spare land and estimated that around 14 percent of GHGs produced by the post-agreement Mexican supply chain were emitted in Central America. By considering telecoupling impacts, it is possible to provide a more realistic estimate of the emissions from food systems. Aguilera and Rivera-Ferre (2022) estimated the environmental impact of three different scenarios in Spain (farm to fork, organic and agroecological) with and without changes in diet (towards a healthy diet). The scenario in which current food demand was supplied through a 100 percent conversion to organic agriculture, assuming a reduced yield of 30 percent, would increase the land needed to produce food in third countries to 10 Mha (from the 9 Mha currently used), externalizing land conversion and associated emissions to those regions. This scenario gives the highest emissions rate: 113 $MtCO_2e$, of which 92.2 $MtCO_2e$ (81 percent) comes from imported food. An agroecological conversion (that is, with no industrial farming) with dietary change would result in net carbon sequestration of 24 $MtCO_2e$, assuming reforestation processes on "spare" land.

10.4. CLIMATE CHANGE IMPACTS AND ADAPTATION WITHIN FOOD SYSTEMS

This section reports on new research on climate change impacts and adaptation in global agriculture and food systems since 2019, including the contribution of Working Group II to the IPCC's Sixth Assessment Report (Bezner Kerr *et al.*, 2022a). It uses a food systems approach (spanning production, processing, distribution, retail, consumption, loss and waste), paying close attention to the interactions and connections between ecosystem services, biodiversity, food security, social inclusion and inequity in food systems (Raworth, 2017; Gerten *et al.*, 2020). Current trajectories of low- and high-intensity food systems and the potential for adaptation in this context will also be discussed.

10.4.1 UPDATE ON GLOBAL AGRICULTURE AND FOOD SYSTEMS STATUS SINCE 2019

According to FAO (2023), global primary crop production was an estimated 9.5 Gt in 2021, up 54 percent from 2000, with four crops (wheat, maize, rice and sugar) making up half of all primary crop production. Vegetable oils, driven by palm oil production, have risen sharply over the last two decades, while meat production has also risen since 2021, to an estimated 357 Mt, half of which is chicken production (FAO, 2023). The increases in agricultural production are attributed to greater use of irrigation, fertilizer and pesticides, with expansion in land area and shifts in practices also a factor (FAO 2023).

Intensified agriculture and food production, particularly livestock, is the primary driver of biodiversity loss globally, with the rate of species extinction estimated to be higher than at any other time in human history (Benton *et al.*, 2021). Expansion of land under agricultural production, combined with the high use of pesticides and fertilizers, is the main cause of biodiversity loss and decline in ecosystem services such as soil fertility, water quality and pollination (Benton *et al.*, 2021).

Food security — which FAO *et al.* (2021 p190) defined as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" — has worsened since 2019, with an estimated 28.9 percent of the global population experiencing moderate to severe food insecurity in 2023 (FAO *et al.*, 2024). The COVID-19 pandemic, combined with conflict, climate impacts and other drivers, led to a sharp increase in the number of people experiencing moderate to severe food insecurity to an estimated 2.33 billion people in 2023, which has remained persistently higher than 2019 levels for the past three years (FAO *et al.*, 2024). Food prices have risen globally, driven by the pandemic, the conflict in Ukraine and inflationary pressures. Low-income countries have experienced the greatest impact, with an estimated 71.5 percent of people not able to afford a healthy diet in 2023, the highest levels since 2017, compared with 6.3 percent in high-income countries (FAO *et al.*, 2024).

10.4.2 CLIMATE CHANGE IMPACTS ON FOOD SYSTEMS

Food production, extreme weather events and food security

Despite overall gains in production, a recent study showed how agricultural productivity growth in the past 50 years has slowed due to climate change impacts, both temperature and precipitation (Ortiz-Bobea *et al.*, 2021). Extreme weather events, such as droughts, floods and marine heatwaves, have increased in frequency since the mid-twentieth century (Seneviratne *et al.*, 2021), leading to sudden food production losses in some regions (Cottrell *et al.*, 2019). There is also increasing evidence of the compounding and cascading impacts of extreme weather events on food systems, with detrimental effects on factors such as food transportation and storage infrastructure, food prices and food safety, in turn leading to rises in acute food security (Bezner Kerr *et al.*, 2022a). The 2015– 2016 El Niño, for example, intensified by global warming (Funk *et al.*, 2018), led to severe droughts in eastern and southern Africa and Southeast Asia, with an estimated additional 5.9 million children underweight (Anttila-Hughes, Jina and McCord, 2021). Another study of 30 African countries between 1993 and 2012 found that children's wasting was significantly related to increased temperature (Baker and Anttila-Hughes, 2020). The same study estimated that by 2100, under RCP 8.5, children's wasting would increase 37 percent in western Africa and 25 percent in southern Africa (Baker and Anttila-Hughes, 2020).

Extreme weather events, such as floods and droughts, contributed to acute food insecurity for over 56 million people in 2022, more than double the previous year (2023). Such events can also reduce the availability of diverse foods in regional markets for small-scale food producers and consumers, particularly in landlocked and low-income countries (Bezner Kerr *et al*,. 2022b). One recent study examining climate data in 19 countries over a 30-year time period, for example, found that higher-than-average annual temperatures were more strongly correlated with lower children's dietary diversity than market access or education (Niles *et al.*, 2021).

Vulnerability, intersectionality and maladaptation

Current research emphasizes that particular social groups, such as women, smallholder farmers, farmworkers and Indigenous Peoples, can be more vulnerable to climate risks within food systems, making them more likely to be food insecure or have their livelihoods negatively impacted (Bacon *et al.*, 2021; Nyantakyi-Frimpong, 2020; Rao *et al.*, 2019a; Tigchelaar, Battisti and Spector, 2020). Notably, these social categories may intersect. For example, farmworkers with a low income may be at greater risk from wildfires, while smallholder women farmers may be more likely to experience food insecurity as a result of flooding than male smallholder farmers, with the specific social categories varying due to political, social and environmental conditions that increase marginalization and risk within food systems (Bezner Kerr *et al.*, 2022a). Importantly, adaptation strategies themselves can actually worsen risks in food systems for marginalized social groups if there are no efforts to address these inequities and differential access to resources in agriculture, fisheries, livestock and aquaculture systems – with increasing evidence of maladaptation in recent years (Bezner Kerr, 2023; Rao *et al.*, 2019b; Huyer and Partey, 2020; Mikulewicz, 2020; Taylor and Bhasme, 2021; Eriksen *et al.*, 2021).

Sustainable Development Goals

Based on current patterns, it is unlikely that SDG 2 (Zero Hunger) will be achieved, partly due to climate change, combined with other drivers of food insecurity and malnutrition (Otekunrin *et al.*, 2019; Singh *et al.*, 2019; Atukunda *et al.*, 2021; Vogliano *et al.*, 2021). Integrated approaches to food systems, which address vulnerabilities, mitigation and adaptation, as well as synergies and trade-offs, would strengthen the potential to meet SDG 2 objectives (Dyngeland, Oldekop and Evans, 2020; Lipper, DeFries and Bizikova, 2020; Vogliano *et al.*, 2021; Grosso *et al.*, 2020).

10.4.3 EFFECTIVE INTEGRATED AND INCLUSIVE FOOD-SYSTEM ADAPTATION STRATEGIES

The intersecting challenges of climate change, biodiversity loss, land degradation, food insecurity, malnutrition, rising rates of diet-related disease and growing economic inequity need to be addressed simultaneously in order to avoid worsening one or more of these challenges. A recent global meta-analysis, for example, found that dramatic declines in insect biodiversity and abundance were associated with an interaction between agricultural intensification and climate change (Outhwaite, McCann and Newbold, 2022). Modelling studies have shown how food security and nutrition can, in turn, be negatively affected by lower insect abundance through a reduction in pollination and subsequent yields of fruits and vegetables (Smith *et al.*, 2022), while overnutrition and diet-related diseases can also be increased by agricultural intensification policies that foster the production of cheap foods high in salt, sugar and fat (Swinburn *et al.*, 2019).

Ecosystem-based approaches that harness biodiversity

Ecosystem-based adaptation approaches that harness and bolster biodiversity have been shown to have multiple co-benefits within food systems, including supporting food security, nutrition, livelihoods and mitigation (Bezner Kerr *et al.*, 2022a; Parmesan *et al.*, 2022). Agroecosystem diversification, including plants, livestock, fish and other species in a range of spatial and temporal arrangements, such as intercrops, crop rotation, agroforestry, flower strips, hedgerows and integrated crop—livestock systems, helps to regulate and support ecosystem services, including soil fertility, pollination, water regulation, the buffering of temperature extremes and pest control (Beillouin, Ben-Ari and Makowski, 2019; Dainese *et al.*, 2019; Kuyah *et al.*, 2019; Tamburini *et al.*, 2020). Recent studies underline that agroecosystem diversification can support yield stability, reduce risk of food loss and overall food security (Roesch-McNally, Arbuckle and Tindall, 2018; Sida *et al.*, 2018; Williams *et al.*, 2018; Birthal and Hazrana, 2019; Degani *et al.*, 2019; Amadu, Miller and McNamara, 2020; Bowles *et al.*, 2020; Li *et al.*, 2020; Rasmussen *et al.*, 2024; Sanford *et al.*, 2021; Zhao *et al.*, 2022). Above-ground diversification practices, such as flowerstrips, hedgerows and crop diversification, support pollination, pest control and water regulation, while below-ground practices, such as the addition of SOC, can enhance below-ground diversification and, in turn, support nutrient cycling, soil fertility and carbon sequestration (Tamburini *et al.*, 2020). In aquatic systems, ecosystem-based diversification practices, such as mangrove restoration, can rebuild fisheries, protect coastal areas from storms and sea-level rise and support local food security and livelihoods, building climate resilience (Donatti *et al.*, 2020; Scotti *et al.*, 2022). A first and second-order meta-analysis of over four decades of research found that diversification in rice production systems provided climate regulation alongside nutrient cycling, biodiversity, soil fertility and other ecosystem services, with "win—win" scenarios in yield and ecosystem services in 81 percent of cases (He *et al.*, 2023). A recent review of 24 studies in 11 countries, spanning 2 655 farms, found that diversification strategies, including livestock, crops, soils, non-crop plants and aquatic systems, had both environmental and social benefits, including yield, food security and human well-being, alongside environmental benefits, such as ecosystem services and reduced externalities, with the use of multiple diversification practices more likely to lead to positive outcomes (Rasmussen *et al.*, 2024).

Agroecology, an approach to food systems that applies both ecological principles, such as supporting biodiversity alongside social principles (HLPE, 2019), is an ecosystem-based adaptation with increased evidence of potential to bolster climate change adaptation (Bezner Kerr *et al.*, 2023). A meta-analysis of 30 long-term experiments in Europe and Africa found that ecological practices (specifically crop diversification, organic matter addition and legume crops) had generally positive effects on staple crop yields (MacLaren *et al.*, 2022). A systematic review of 50 studies in LMICs found that, under smallholder farming conditions, agroecological practices improved climate change adaptation indicators while supporting yield and food security (Dittmer *et al.*, 2023). Practices that showed consistent climate-adaptive capacity included legume diversification, integrated pest management and the use of organic amendments. Agroecological approaches go beyond the production system, however, by taking a holistic approach and applying social principles, such as knowledge co-creation, supporting regional and local markets that connect producers with consumers, reducing reliance on purchased inputs and addressing inequities (HLPE, 2019). A systematic review found that agroecological practices had positive impacts on food security and nutrition in 78 percent of studies, with more complex agroecological systems more likely to have positive outcomes (Bezner Kerr *et al.*, 2021). A recent review of studies in 17 African countries with high levels of food insecurity found that agroecological practices improved agroecosystem resilience to climate events, while positively affecting other SDGs, in 79 percent of studies, including food security, biodiversity and reducing poverty (Madsen *et al.*, forthcoming). Another study of nine farmer organizations across the United States and Canada found that farmer networks were a significant factor in predicting the use of adaptive agroecological practices (White *et al.*, 2023).

Multisectoral approaches to addressing climate risks to food security and nutrition

The complex and intertwined nature of threats to food security and nutrition requires a multisectoral approach across health, food and information systems (Tirado *et al.*, 2022). Increasing access to health services, water and sanitation is another important dimension of multisectoral approaches to reducing climate risks to food security and nutrition (Tirado *et al.*, 2022). Supporting nutrition-sensitive food systems through policies and programmes that increase production of and access to affordable, locally produced, diverse, healthy foods for vulnerable groups can be an important way of reducing climate risks for both local producers and consumers. Social protection programmes, such as school feeding programmes for low-income households that source diverse foods from local farmers using climate-resilient production methods, for example, are one such pathway (Dyngeland, Oldekop and Evans, 2020; Tirado *et al.*, 2022). Adaptive social protection programmes can be combined with disaster risk reduction and climate adaptation programmes to implement preventative and adaptive measures, such as supporting water catchment or soil moisture conservation in the face of drought (Tirado *et al.*, 2022).

Urban and peri-urban agriculture

As the majority of people now live in urban and peri-urban areas, there is a greater need to consider urban and peri-urban food systems in adaptation strategies (FAO *et al.*, 2023). Previous IPCC reports have highlighted the potential of urban agriculture as an adaptation strategy (IPCC, 2019b). Recent research notes the need to address questions of governance of urban agriculture, such as the right to green urban space for locally accessible diverse food, and other benefits of urban agriculture, such as mental health, community building, livelihoods and reducing urban heat islands (Halvey *et al.*, 2021; O'Sullivan *et al.*, 2019; Siegner, Sowerwine and Acey, 2018; Titz and Chiotha, 2019).

Inclusive multisectoral adaptation strategies as enabling conditions

Given the heightened vulnerability of particular social groups to climate risks in food systems, an important overall strategy for adaptation is inclusive approaches that explicitly address gender, racial, income and other social inequities in governance, access and control over resources (Blesh *et al.*, 2019; Eriksen *et al.*, 2021; Garcia *et al.*, 2021; Rao *et al.*, 2019b; Tavenner *et al.*, 2019). Such strategies might include participatory, inclusive decision-making in adaptation programmes, alongside efforts to explicitly change social norms, practices and rules related to marginalized groups, to enable them to have greater access to resources and increase their adaptive capacity (Bezner Kerr *et al.*, 2022b; Ziervogel, 2019). Integration of humanitarian and peacebuilding initiatives may also be critical to ensure that climate change adaptation can effectively be implemented, as conflict can interact with and compound climate impacts on food security and nutrition outcomes (FAO *et al.*, 2021; Tirado *et al.*, 2022).

Climate services and early warning systems within food systems can be an important adaptation strategy, but may not be available to or usable by vulnerable groups, such as women, Indigenous Peoples, farmworkers or low-income households (Greene and Ferguson, 2024). Recent research suggests that if climate services and early warning systems are adapted to the needs of particularly vulnerable groups through participatory co-design and implementation, they can strengthen such groups' capacity and reduce their climate risk (Camacho and Conover, 2019; Gumucio *et al.*, 2020, 2022; Sultan *et al.*, 2020). However, research is still needed on how to effectively reach and provide climate services to those who are most marginalized and at greatest risk (Greene and Ferguson, 2024; Gumucio *et al.*, 2022; Nsengiyumva *et al.*, 2022).

Policy, planning and governance

There has been an increase in research on how adaptation policy and planning is undertaken in food systems, testing inclusive participatory methods such as community-based "anticipatory adaptation" that combine future scenarios, different adaptation pathways and stakeholder dialogue (Bezner Kerr *et al.*, 2019; Neset *et al.*, 2019; Rahman and Hickey, 2019; Work *et al.*, 2019; Butler *et al.*, 2020; Piggott-McKellar, McNamara and Nunn, 2020; Westoby *et al.*, 2020). These promising policy tools take into account trade-offs, mitigation—adaptation interactions and ongoing evaluation (Holsman *et al.*, 2019; Rahman and Hickey, 2019; Work *et al.*, 2019; Butler *et al.*, 2020). Participatory governance approaches include marginalized groups in the decision-making structure and try to balance land and water rights, sociocultural dimensions and food security (Holsman *et al.*, 2019; Rahman and Hickey, 2019; Butler *et al.*, 2020). While there are clear biophysical and political-economic limits to adaptation (Nelson *et al.*, 2024), sociocultural, political, economic and agroecosystem contexts interact, making particular social groups more vulnerable to these limits in a given food-system context (Bezner Kerr *et al.*, 2022b). There is evidence of the potential to redirect existing policies and programmes to address climate change risks. One study in the United States, for example, found that agricultural practices (between 2009 and 2018) had the most potential to improve climate resilience in production and accounted for 2—27 percent of annual funding for the Environmental Quality Incentives Program (a programme for landowners to gain support based on practices) and around 0.08 percent of total annual US Department of Agriculture expenditures (Basche *et al.*, 2020). There is evidence that addressing unequal power dynamics in food systems governance will be a key aspect of opening up transformative pathways towards climate-resilient and equitable food systems (Bezner Kerr *et al.*, 2022b).

10.4.4 SYNERGIES AND TRADE-OFFS BETWEEN CLIMATE OPTIONS IN FOOD SYSTEMS AND THE SUSTAINABLE DEVELOPMENT GOALS

Climate options in food systems have the potential to generate significant synergies across various SDGs, but some can also involve trade-offs (IPCC, 2023). Understanding these linkages is crucial for policymakers to design strategies that promote climate change mitigation, adaptation and sustainable development.

Recent literature has analysed the linkages between climate actions in food production with SDGs and found that synergies with SDGs are always greater than trade-offs. However, these linkages are very context dependent (Some, 2024; IPCC, 2022, 2023). Trade-offs identified include high upfront costs, the requirement for skilled labour to adopt new practices, and a lack of access to information and finance. Halsnæs *et al.* (2024) highlight the importance of considering context-specific factors and potential negative impacts on equity when implementing specific options. Roy *et al.* (2022) noted that adaptation programmes that are consciously designed to advance gender equality often have positive links to SDG 5 targets. However, if gender-focused targets are not intentionally brought in at the prioritization, design, planning and implementation stages, then adaptation actions can exacerbate inequalities. For instance, while conservation agriculture can empower women by creating more decision-making roles in some cases, it can also increase their workload when their male counterpart migrates. Factors such as low income and limited access to information can further hinder women's participation in such adaptation programmes. Studies also suggest measures to tackle and minimize these trade-offs, such as providing gender-sensitive training and financial support to farmers, investing in research and innovation, and enhancing stakeholder partnerships (Some, 2024; Roy *et al.*, 2022).

Demand-side actions, such as shifting to sustainable diets and reducing food waste, have significant potential for climate change mitigation and achieving multiple SDGs. The literature shows that these options have synergies with various SDGs, including SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water) (IPCC, 2023, 2022; Some *et al.*, 2022). For instance, shifting to diets with less red meat and processed food can improve public health (SDG 3), while reducing food waste can lead to more efficient resource use (SDG 12). However, studies also identified potential trade-offs, such as the possibility of exacerbating poverty (SDG 1) if demand for certain agricultural products declines, or rebound effects where cost savings from reduced food waste are spent on other consumption with negative environmental impacts (Some *et al.*, 2022).

Overall, it is crucial to identify and address potential trade-offs to ensure that these actions contribute to sustainable development and leave no one behind. Further research is needed to delve deeper into the specific trade-offs of climate action in food systems, such as impacts on poverty (SDG 1) and rebound effects (SDG 12). Analysing implementation barriers to food-system climate options, such as access to finance and technology, is crucial, along with an evaluation of policy effectiveness and an exploration of innovative financing mechanisms to reduce inequality. Expanding research to quantify these synergies and trade-offs in diverse contexts will ensure comprehensive and equitable climate action for all.

References - Section 10

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11. Policy and governance

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11.1. IDENTIFYING BARRIERS AND ENABLING MULTISCALE GOVERNANCE CRITICAL TO ACHIEVING SUSTAINABLE AND CLIMATE-SMART AGRIFOOD SYSTEMS

11.1.1 LAND USE AND AGRICULTURE

Food production is a fundamental part of agrifood systems and the main objective of many land-based systems. However, the implementation of good practices in land management, including agriculture and livestock systems, that contribute to climate change mitigation faces several barriers and challenges. These are often linked to specific national and local circumstances that limit the technical potential for climate change mitigation identified by modellers at a global level (IPCC, 2022), including technological, ecological, institutional, economic and sociocultural aspects. Overcoming these barriers requires time, financing and capacity support, as well as proposals for case-specific mitigation measures and approaches (Bustamante *et al.*, 2014). Some of the more prominent barriers are listed below (**Table 11.1**), grouped into sociocultural, financial and economic, institutional and political, technological and ecological hurdles (Vidal *et al.*, 2022).

TABLE 11.1. Synthesis of the main barriers to mitigation in the AFOLU sector

Type of barrier	Barriers
Sociocultural	Different epistemic/ontological views of agriculture or semi-natural versus nature
	Underlying narratives behind initiatives pursue different goals
	Lack of skilled workers
	Limited or no access to extension services
	Lack of coordination in agricultural associations and networks
	Limited or no access to education
	Lack of environmental awareness
Environment	Limited or no access to finance
	Limited or no access to markets
	Limited or no access to insurance
	Opportunity cost
	Poverty
	Uneven share of benefits
Institutional and political	Land tenure (poor or non-existing schemes)
	Political instability
	Corruption and lack of trust on government
	Inability of states to enforce law
	Lack of political commitment and ambition
	Governance misalignment
	Lack of transparency
	Lack of integration of local communities in decision-making
	Lobbying

Type of barrier	Barriers
Technological	Land management and agricultural practices depend on local conditions
	Limited or no access to inputs (seeds and fertilizers)
	Access to adequate technology (tools and machinery)
	Existence of irrigation infrastructure
	Lack of high-quality data on carbon emission baselines
	Complexity of monitoring, reporting and verification of emissions and removals

Source: Adapted from Vidal, A., Sanz, M.J., García de Jalón, S. & Van de Ven, D.-J. 2022. Planting the Seeds of Mitigation: Climate Governance Gaps and Options for the Land Use Sector. Deliverable 6.1a report. Brussels, NDC-Aspects Consortium. https://ndc-aspects.eu/publications/deliverables

The current governance landscape addresses these complex, sectoral barriers in several ways, including by providing guidance and signalling to actors, setting rules to facilitate collective action, enhancing transparency and accountability (including compliance), offering support for means of implementation (capacity building, technology and finance), and promoting knowledge diffusion and learning. However, gaps remain, especially with regard to transparency and appropriate rules and standards, as well as the complexities of the land-use sector and its linkages to agrifood systems. This is particularly evident when considering the means of implementation (particularly in relation to Article 6 of the Paris Agreement) and the proliferation of disconnected initiatives that often create a burden for implementers rather than enabling them. The key governance gaps identified relate to: i) the need to signal realistic mitigation potential for the sector and characterize trade-offs (Vidal *et al.*, 2022); ii) the misalignment of current monitoring, reporting and verification standards; iii) the remaining uncertainties and lack of trust surrounding carbon markets under the Paris Agreement; iv) the insufficiency of funds mobilized to date and enabling conditions for their deployment; v) the limitations of global assessments of the mitigation potential of the sector, which are often top-down and unrealistic; and vi) the duplication of effort and disconnection among various initiatives across the sectoral governance landscape.

Nonetheless, some options remain with a view to closing gaps in sectoral governance. The adoption of consistent standards across existing institutions on monitoring, reporting and verification, aligned with the rules and modalities adopted by the UNFCCC, could greatly enhance transparency, the comparability of efforts and the efficacy of climate action. The creation of sector-wide collaborative partnerships could enhance the complementarity of financing mechanisms and increase the efficiency of resource allocation towards mitigation, without ignoring adaptation needs, based on best available knowledge, both top down and bottom up. Access to and orchestration of the best available knowledge could be served by a platform (or joint working group) to continuously maintain an in-depth technical dialogue between modellers and GHG inventory communities, illustrating the realistic mitigation potential and the potential trade-offs of the sector, and cautioning about the limitations of global assessments under the umbrella of the IPCC. This could tie in with public-private partnerships, including engagement with stakeholders that could provide guidance on the design of mitigation- and adaptation-integrated solutions and pathways better adapted to sectoral context and implementation scales.

However, no solution will work if the underlying risk aversion of donors and investors and the short-term nature of targets and goals remain. In particular, the complexity of the biological processes involved and the drivers of emissions and removals in the sector, can result in large uncertainties in emissions and removals, non-additionality, reversals and double counting. Gaining greater understanding of this complexity and finding affordable "science-based" ways of minimizing risks will be critical to informing the necessary climate investment decisions needed to address climate risk and promote resilience.

11.1.2 GOVERNING FOOD SYSTEMS WITH A HOLISTIC APPROACH

Advances have been made on land use and agriculture governance research, but key gaps persist thanks to the complexities of agrifood systems. Food systems encompass complexities that pose even more challenges and add several dimensions. However, according to Janing, Fofiri Nzossié and Racaud (2023), the functional, accountable and legitimate governance of food systems must consider several essential dimensions: complexity of the stakes and interactions between fields and context-specific phenomena; autonomy, adaptability and inventiveness; responsiveness to respond promptly to multiple requests; structuring conditions to allow for a way out of situations of withdrawal, deadlock, protection, political confrontation and inaction; and inclusivity to sidestep purely technocratic and routine.

It has to be acknowledged that there is a tension between the concentration of power of international players (transnational corporations, state governments and regional agro-exporting organizations) and the specificities of local contexts when approaching food systems. Therefore, successful transformation of agrifood systems requires the co-construction of innovative arrangements between actors in the system, particularly between academics, community practitioners and local authority players.

Several authors identify a need to transcend multiple governance levels and sectors when developing food policy integration that pivots on food systems (Janing, Fofiri Nzossié and Racaud, 2023; Kang, Roggio and Luna-Reyes, 2022). Local, state and national governments must create political space for public debate on bettering food systems and involving the private sector in all forms to avoid policy inertia, while mitigating their asymmetrical power influence on policymaking (Summerhayes and Baker, 2024). Better multi-governance could enable collaborative food policy governance involving multiscalar governments, food industries and civil society in policy development and implementation. However, no single model will work for all. Food systems localization, which often seeks to enhance food security, should be focused on mitigating the growing crisis of food insecurity in its different dimensions – availability, accessibility, utilization, stability and sustainability on different governance scales and in different sociocultural contexts (Tacoli, 2020). New cooperation between local actors and governmental management structures have emerged — mostly on an informal, ad hoc basis during the recent crisis — but without further institutionalization, built-up capacities may be lost after (Polman *et al.*, 2023). This reinforces the idea that in all models, lines of responsibility for the governance and implementation of food systems policies need to be clearly defined and legislated.

11.2. ENABLING ENVIRONMENT FOR CLIMATE ACTION IN AGRIFOOD SYSTEMS

To address the global climate crisis, 196 parties from developed and developing nations adopted the landmark Paris Agreement in 2015. The agreement sets three overarching goals: to collectively pursue efforts to limit the increase in global temperature to 1.5 °C compared with pre-industrial levels; to enhance adaptive capacity and resilience to climate change; and to make financial flows consistent with low-emission, climate-resilient development pathways. Article 4 of the agreement requires all parties to set out their best efforts to address climate change in an NDC, a national climate plan they must submit to the UNFCCC every five years.

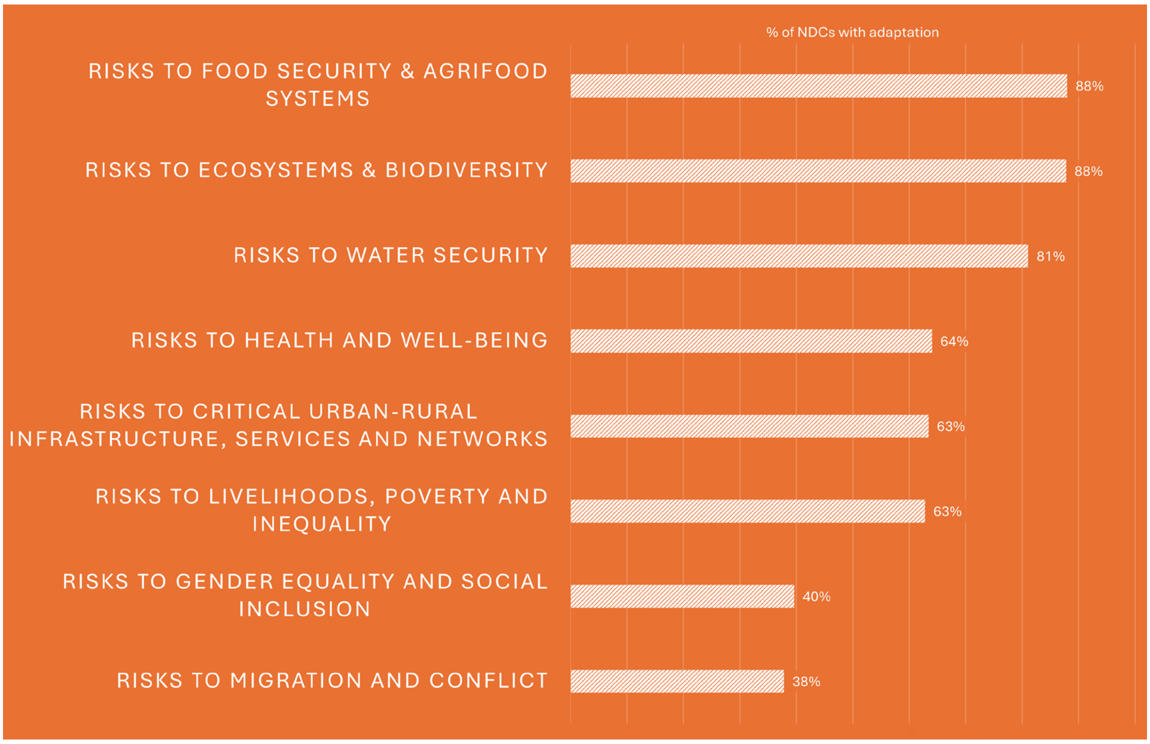
To understand the extent to which agrifood systems are prioritized within national climate change plans, FAO screened 167 NDCs submitted to the UNFCCC. European Union NDCs were treated as a single NDC. The analysis, therefore, encompassed 194 parties to the Paris Agreement and 193 countries as of 1 January 2024. This section presents the results of that FAO analysis (Crumpler *et al.*, 2024).

11.2.1 CLIMATE RISK CONTEXT INFORMING NATIONAL CLIMATE PLANS

Risks to food security and the loss of ecosystems and biodiversity are the most frequently cited climate-related risks in the NDCs (88 percent of NDCs), particularly in sub-Saharan Africa (**Figure 11.1**). Other key representative risks overlap with agrifood systems and inform adaptation responses globally, including risks to living standards and inequality (82 percent) and risks to water security (82 percent) associated with climate change. Around two-thirds of countries cite climate-related risks to human health (64 percent) and risks associated with critical infrastructure and services (63 percent), while around one-third note risks to peace and migration (38 percent).

Within agrifood systems, many countries report observed and/or projected climate-related impacts or risks in crop-based systems (67 percent of NDCs), including changes in crop yields and productivity; incidence of pests, diseases and weeds; altered crop phenology; impacts on soil and water for agriculture; and changes in area suitable for crop production. Almost half of all countries cite climate-related impacts in livestock-based systems (45 percent), including impacts on rangelands, feeds and forages; changes in animal productivity and livestock distribution; incidence of diseases and vectors; animal heat stress and mortality; and impacts on water resources for livestock. Nearly half of all countries report climate-related impacts in forest systems (45 percent), including range reductions and shifts; tree mortality; changes in physiology and phenological responses; and reduction in the provision of forest (food and non-food) products. Almost half of all countries mention climate-related impacts in ocean-based and inland fisheries and aquaculture systems (45 percent), including phenological shifts and trophic mismatches; changes in species abundance and distribution; harmful algal blooms; coral bleaching; reductions in fisheries production and productivity; and a reduction in freshwater and coastal water quality for fisheries. Overall, least developed countries and low-income countries cite climate-related vulnerabilities in agrifood systems more frequently – across every agrifood subsystem – than the global average.

FIGURE 11.1. Representative climate-related key risks (observed and/or projected) relevant to agrifood systems, by type (percentage of nationally determined contributions with an adaptation component)

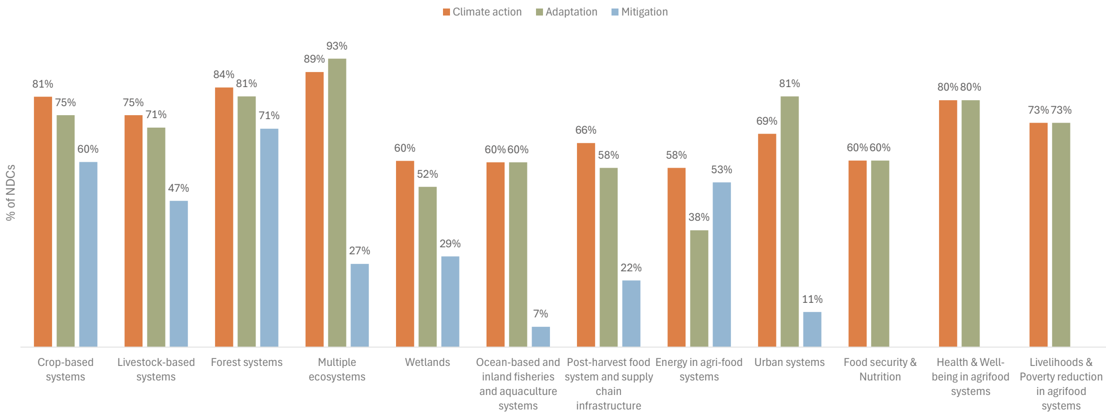


Source: Crumpler, K., Wybieralska, A., Roffredi, L., Tanganelli, E., Angioni, C., Prosperi, P., *et al.* 2024. Agrifood systems in nationally determined contributions: Global analysis – Key findings. Rome, FAO. https://doi.org/10.4060/cd3210en

11.2.2 PRIORITY AGRIFOOD SYSTEMS FOR CLIMATE ACTION WITHIN NATIONAL CLIMATE PLANS

Almost all countries identify agrifood systems as a priority for climate change adaptation (94 percent) and mitigation (91 percent) in their NDCs. Within agrifood systems, priority areas for climate action (**Figure 11.2**) span all agricultural and land-use sectors, including crop-based systems (81 percent of NDCs), livestock-based systems (75 percent), ocean-based and inland fisheries and aquaculture systems (60 percent), forest systems (84 percent), multiple ecosystems (89 percent) and wetlands (60 percent). They also include energy use and industrial processes in agrifood (66 percent) and the post-harvest side of agrifood systems and supply-chain infrastructure (58 percent). Climate action priorities also aim to address the broader economic, societal and natural environments in which these diverse agrifood systems are embedded, including food security and nutrition (60 percent), health and well-being (80 percent), and livelihoods and poverty alleviation in agrifood systems (73 percent).

FIGURE 11.2. Priority agrifood subsectors/systems for climate action, by climate objective (percentage of nationally determined contributions)



Source: Crumpler, K., Wybieralska, A., Roffredi, L., et al. 2024. Agrifood systems in nationally determined contributions: Global analysis – Key findings. Rome, FAO. https://doi.org/10.4060/cd3210en

Among the top 15 climate action areas for agrifood systems identified in the NDCs, the majority are ecosystem-based approaches and focus specifically on leveraging the carbon sequestration and adaptive benefits provided by terrestrial, forest and ocean, and coastal ecosystems (**Figure 11.3**). Other prioritized climate action areas include on-farm soil and water moisture conservation; irrigation and water harvesting; agroforestry; climate-tolerant crops and livestock breeds; and investments in productive infrastructure, assets and urban—rural networks. Many of the action areas identified are consistent with those proven to have the highest technical and financial mitigation potential in the sector (Roe *et al.*, 2021) and are aligned with the most effective and available adaptation options when contextualized to the local level (FAO, 2023). However, some key climate action areas (Lee *et al.*, 2023) are still underrepresented, including food loss and waste reduction, shifting towards sustainable healthy diets, and sustainable and adaptive fisheries and aquaculture management.
The NDCs also highlight the increasingly important role of on- and off-farm livelihood diversification as a risk mitigation strategy, as climate change will drive economic transitions to reduce the impact of climate-induced income shocks and build longer-term resilience to climate and other risks.

FIGURE 11.3. Top 15 agrifood system climate solutions promoted in nationally determined contributions (percentage of nationally determined contributions)

Source: Crumpler, K., Wybieralska, A., Roffredi, L., Tanganelli, E., Angioni, C., Prosperi, P., *et al.* 2024. Agrifood systems in nationally determined contributions: Global analysis – Key findings. Rome, FAO. https://doi.org/10.4060/cd3210en

NDCs can provide insights into national climate-resilient development pathways. There is increasing evidence that agriculture and forestry sectors offer more potential for climate-resilient development than others when deliberate decisions are made to address long-term structural vulnerabilities, attention is paid to mitigation–adaptation mismatches between and across sectors, and maladaptation is avoided (Birkmann *et al.*, 2022). Around one-third of all countries explicitly recognize the co-benefits of climate action in agrifood systems for achieving the SDGs in their NDCs (**Figure 10**), particularly SDG 2 (Zero Hunger), SDG 1 (No Poverty) and SDG 15 (Life on Land). At the same time, around half of all countries explicitly identify synergies between adaptation and mitigation actions that are unique to agrifood systems (Crumpler *et al.*, 2024).

11.2.3 AGRIFOOD SYSTEM MITIGATION AND ADAPTATION TARGETS SET IN NATIONAL CLIMATE PLANS

Only 19 percent of NDCs include long-term mitigation goals in the AFOLU sector, typically set to mid-century or beyond. The large majority of countries (83 percent of NDCs) set near-to-medium-term, economy-wide GHG targets covering the AFOLU sector, while fewer than half (40 percent) include sector-specific GHG targets for the AFOLU sector. A significant share – up to 92 percent — of GHG emission reductions in the AFOLU sector depend, however, on the flow of international support, including finance, technology transfer and capacity building. Around three-quarters (74 percent) of AFOLU sector-specific GHG targets are partially conditional, while a small share (18 percent) is completely conditional, on the provision of international support. Only a tiny fraction (8 percent) of GHG emission-reduction targets for the AFOLU sector will be achieved through domestic means of implementation. To date, 53 percent of parties indicate in their NDCs that monitoring, reporting and verification systems are under development to track mitigation progress (UNFCCC, 2024).

Around half of countries include quantified and time-bound adaptation targets (45 percent) and indicators (46 percent) in their NDCs for tracking adaptation in agrifood systems. Considering the relevance of adaptation indicators for agrifood systems included in the NDCs for measuring progress against the four domains of the Global Goal on Adaptation Framework and, in particular, target b on food and agriculture, an uneven picture emerges (UNFCCC, 2023a; Distefano, 2023). Three-quarters (75 percent of indicators) are designed to measure changes in adaptive capacity and resilience in agrifood systems, while approximately one-quarter (22 percent) measure changes in ecological and socioeconomic vulnerability levels, and very few (3 percent) measure impacts of adaptation in agrifood systems on sustainable development. Furthermore, there are no standalone adaptation indicators included in the NDCs to measure climate risks or impacts on agrifood systems (0 percent), such as exposure to agricultural drought or crop pests and diseases, indicating gaps in the explicit climate relevance of adaptation indicators in agrifood systems.

In addition, the overwhelming majority of adaptation indicators included track the immediate outputs of adaptation (74 percent of indicators), while some measure adaptation planning processes (18 percent) and very few measure near-to-medium-term adaptation outcomes (4 percent) or the longer-term sustainable development impacts of adaptation in agrifood systems (3 percent). Similarly, the indicators included in the NDCs predominantly measure adaptive (74 percent) and absorptive (23 percent) capacities in the face of climate risk in agrifood systems, while very few (3 percent) measure the capacity to transform. This finding concurs with the outcome report of the first UNFCCC Global Stocktake Report (Decision/CMA.5), which found that most of the observed adaptation responses to date are incremental and fragmented in nature (UNFCCC, 2023b). It stressed that achieving the Global Goal on Adaptation would entail a combination of incremental and long-term transformational changes across key sectors and systems, including agrifood systems. To date, around two-thirds of all parties (68 percent) report on efforts to establish or strengthen monitoring and evaluation systems to track adaptation in their NDCs (UNFCCC, 2024).

11.2.4 CROSS-CUTTING POLICY INSTRUMENTS TO ENABLE CLIMATE ACTION IN AGRIFOOD SYSTEMS

A range of factors, including governance, finance knowledge and capacity, can either enable or limit the effectiveness of climate change planning and implementation (New *et al.*, 2022). Information programmes and training (62 percent) are top of the list of necessary policy instruments in the NDCs for enabling effective climate action in agrifood systems.

11.2.5 CLIMATE FINANCE NEEDS ESTIMATED FOR AGRIFOOD SYSTEMS

Without accelerated climate finance, delayed emission reductions will push critical ecosystems and human systems, including agrifood systems, beyond their environmental and social tipping points. Current global financial flows to agrifood systems are strikingly insufficient, receiving just 4.3 percent of total project-level climate finance tracked in 2019—2020 (CPI, 2023a). Merely 0.8 percent is reaching small-scale agriculture, covering only a small fraction of actual needs (CPI, 2023b). The latest estimates state that climate finance for agrifood systems must increase at least 40-fold from current levels to reach the most conservative estimate of needs, in the order of USD 1 trillion dollars annually (CPI and FAO, 2024). Instead of rising to meet these needs, global trends over the past two decades reveal a sharp decline in the proportion of climate-related agrifood system development finance flows (FAO, 2024). Closing the widening finance gap will require incentivizing agrifood systems transformation through enabling policies and innovative public—private investment.

The volume of climate finance needs estimated for agrifood systems in the NDCs reflects only a fraction – one-sixth – of what is likely to be needed. Agrifood system climate needs stated in the NDCs extrapolated to the global level amount to an annual average of USD 201.5 billion through 2030, representing only a portion of the estimated USD 1.15 trillion needed yearly (CPI and FAO, 2024). This suggests that NDCs are underestimating the investment needed for agrifood system climate solutions, presenting a missed opportunity when it comes to influencing the flow of international finance support to developing countries and formulating reliable investment plans.

Sixty-five percent of climate actions in agrifood systems costed in the NDCs are conditional on the provision of international finance, while one-third are expected to be financed domestically. Low-income countries (67 percent of total finance), least developed countries (69 percent) and SIDS (66 percent) also rely more heavily on international climate finance than domestic finance for agrifood systems, indicating that these low-income and special country groups are particularly dependent on the provision of international support to address climate change in agrifood systems (CPI and FAO, 2024).

Currently, only one-third of NDCs provide specific climate finance information related to agrifood systems. This significant data limitation prevents an accurate understanding of the magnitude of climate finance needed for agrifood systems globally and its distribution across regions, subsectors and climate objectives. Consequently, the data quality gap limits the opportunity for NDCs to serve as reliable policy signals capable of directing the flow of climate finance to where it is needed most. Future NDC iterations should provide more quantified and granular information to represent the true cost of climate action in agrifood systems. More effort should be dedicated to building countries' bottom-up capacity, as well as the availability of data sources and standardized methodologies, to estimate agrifood climate finance needs in the NDCs, so that they can serve as national blueprints for public- and private-sector investment.

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12. Pending issues not covered in this report

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It has not been possible to cover all relevant topics in this report, such as the economic aspects of interactions between agriculture, food systems and climate change. Nonetheless, such topics will be discussed at an international scientific meeting planned for 2026. The meeting will bring together experts from around the world to discuss the findings of this report, as well as other subjects, to identify the implications of the research findings and gaps. The meeting also aims to provide up-to-date scientific evidence for use by FAO and the wider research and policy communities, and to synthesize information to inform forthcoming IPCC reports on agriculture, food systems and climate change interactions.

Question to be addressed at the meeting will revolve around how climate change affects agriculture and food systems, and vice versa. Topics not specifically covered in this report which might be discussed at the meeting are:

Further climate change impacts on agriculture:

- Crop yields: Extreme weather events, such as droughts, floods and heatwaves, can reduce crop yields.
- Soil health: Drought and heavy rainfall can degrade soil health and lead to soil erosion.
- Heat stress: Heat stress can affect the appetite and milk production of dairy cows.
- Pests: Period of drought can increase the breeding of vectors that spread pests.
- Water scarcity: Access to water will determine crop choice, land management and a range of adaptation options (see **Box 12.1**).

Climate change impacts the agricultural economy:

- Food costs: Rising food costs can increase the vulnerability of developing countries.
- Farm revenue: Reduced crop yields can mean less revenue for farms.

- Labour productivity: Exposure to extreme heat can cause occupational illnesses, increase the risk of injury and lower productivity.

How farmers respond to climate change:

- Farming exits: Farmers may switch crops, change productive practices or even move away from agriculture entirely.
- Barriers to responding to climate change: Poorly developed input and output markets and a lack of insurance, finance or institutions can prevent resource reallocation.

A wider list of topics will be identified at the Expert Meeting.

12.1. WATER SCARCITY

BOX 12.1. Water scarcity and agriculture in Latin America and the Caribbean

Latin America and the Caribbean is probably the most diverse region on the planet, with climatic conditions that range from the hot and humid Amazon River basin to the dry and desert-like conditions of northern Mexico and northern Chile. What is more, it is home to about half of the world's remaining tropical forests, with major biomes including the Amazon, along with drier forests/woodlands and savannahs, such as the Gran Chaco (spanning parts of Argentina, the Plurinational State of Bolivia, Brazil and Paraguay), the Cerrado (in Brazil) and the Chiquitano (in the Plurinational State of Bolivia and Brazil).

While known for its rainforests, two-thirds of the Latin America and the Caribbean region has a semiarid to arid climate: central and northern Mexico, northeast Brazil, central and southern Argentina, central and northern Chile, and some parts of the Plurinational State of Bolivia and Peru (Mahlknecht *et al.*, 2020). According to FAO (n.d.), drylands are characterized by a scarcity of water, which affects both natural and managed ecosystems and constrains the production of livestock, as well as crops, wood, forage and other plants, and affects the delivery of environmental services. Drylands have been shaped by a combination of low precipitation, drought and heatwaves, as well as human activities such as fire use, livestock grazing, the collection of wood and non-wood forest products, and soil cultivation.

In this context, Latin America and the Caribbean, like other regions of the planet (especially the African continent), faces a series of challenges in managing its agroecosystems, particularly with regard to water scarcity and drought. While these phenomena have always been present, they are becoming more frequent and intense due to the effects of global climate change. Droughts vary in duration, severity and spatial coverage, and the impacts of the water deficit vary according to the specific event. Droughts are generally classified as meteorological, agricultural, hydrological or socioeconomic.

Regardless of type, droughts always cause stress and damage agricultural production. For instance, drought-induced production losses in Brazil were observed in 2012 and 2016, with respective production declines of 62.4 percent and 48.2 percent for beans, 46.6 percent and 42.3 percent for maize, and 34.3 percent and 15.6 percent for cassava (Carvalho *et al.*, 2020). Economic losses in Brazil in 2020 were USD 3 billion (Aon Benfield UCL Hazard Research Centre, 2020). Similar losses were observed in other Latin American countries, such as Argentina, El Salvador, and Guatemala, which experienced severe agricultural losses due to droughts in 2018, totalling about USD 6 billion (Aon Benfield UCL Hazard Research Centre, 2019). Drought-related global economic losses from 2000 to 2020 are estimated at USD 438 billion (Aon Benfield UCL Hazard Research Centre, 2020).

Increasing aridity, enhanced warming and rapidly growing human population will exacerbate the risk of land degradation and desertification soon in the drylands of developing countries, where 78 percent of dryland expansion and 50 percent of population growth in dryland areas will occur under RCPs (RCP 8.5, for example). For Latin America and the Caribbean, in 2071—2100 relative to 1961—1990, based on the UNEP Aridity Index, the RCP 8.5 scenario shows an increase in arid and semiarid conditions in central Mexico and isolated regions of southern Peru and Central America, Northeast Brazil (concurring with Marengo, Torres and Alves, 2021) and northern Argentina. These climatic fluctuations may be most pronounced in the poorest regions with high levels of chronic undernourishment and a great degree of instability. Food-price fluctuations already pose a risk to vulnerable populations and are expected to worsen with climate change (Maia *et al.*, 2023).

Projections by Chai *et al.* (2021) identified in Coupled Model Intercomparison Project (Phase 6) (CMIP6) simulations consistently see drying trends, based on the UNEP Aridity Index, in the drylands of central North America and central South America under both SSP3-7.0 and SSP5-8.5 scenarios. The authors explain that such Aridity Index decreases driven by elevated GHG emissions are mainly caused by the increase in air temperature, implying that the land precipitation increase could not keep pace with the growing evaporative demand associated with GHG-dominated warming. However, the model-projected trends of land aridity in the 21st century may contain significant uncertainty. The largest expansion of drylands has occurred in semiarid regions since the early 1960s. Future aridity changes suggest society is likely to face more pressing environmental challenges (Huang *et al.*, 2017).

Dryland expansion will lead to reduced carbon sequestration and enhanced regional warming. Increasing aridity, enhanced warming and the rapidly growing population will exacerbate the risk of land degradation and desertification in the near future in developing countries.

Water governance is institutionally organized in most countries in Latin America and the Caribbean, but fragmented, lacking improvements in policy coherence, integrity, transparency, stakeholder involvement and financing (Neto *et al.*, 2018). Governance of water and territory, associated policies and management systems needs stronger integration with other sectoral policies, such as agricultural and energy (Mahlknecht *et al.*, 2020). River basin organizations may have a central role in improving governance, but they are not implemented in all countries in Latin America and the Caribbean and vary widely in maturity. Securing investments and appropriate governance for adaptation, such as better drought stress management, infrastructure upgrades and operational optimization, are necessary to improve water security in the medium to long term. Maintaining "business as usual" in technological development and appropriation, sources of funding and resource allocation will not achieve the desired adaptation goals. Innovation in financing is mandatory to achieve sustainable water security in Latin America and the Caribbean drylands (Lentini, 2022).

Empowering the vulnerable smallholder farmers of the Latin America and the Caribbean drylands to promote equity in access to water, financing, technology and other resources is a governance challenge. Government and other institutional recognition of such communities and their important role in the regional economies is the first step towards this goal. Often, water governance frameworks do not consider these highly numerous farmers (Tsuyuguchi *et al.*, 2020; Ocampo-Melgar *et al.*, 2022).

The management of stresses caused by drought in agriculture can occur in different ways, such as the genetic improvement of crops, cultivated plant resistance mechanisms (including escape, avoidance and tolerance mechanisms), seed priming, plant growth regulators, osmoprotectants, fertilization management (application of certain elements, such as potassium, selenium and silicon), hydrogel, and microorganism manipulation, as well as management practices that include soil and the diversity of cultivated and/or native plants or animals (Adeyemi *et al.*, 2020; Seleiman *et al.*, 2021). Many of these possibilities are still not commercially viable or are difficult to adopt in the drylands of Latin America and the Caribbean, especially in developing countries, where small farmers, who do not have access to technical assistance, financial resources or adequate public policies, predominate.

Adapted management practices for the drylands of Latin America and the Caribbean involve some fundamental principles, especially for the development of sustainable dryland farming systems. These include, for example, optimizing the fit between crop growth cycle and available moisture; weed control; optimized plant population density and spatial arrangement of plants; soil fertility management with regard to the water regime; control of soil biotic stress factors that inhibit root development; improved forage/livestock/grain integration and rotation; better soil and water conservation practices and associated reduced tillage systems; increased soil organic matter content; and the enhancement of crop and livestock diversification (Maia *et al.*, 2023).

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