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Interim report

# Barriers to mitigating emissions from agriculture

## Analysis of mitigation options, related barriers and recommendations for action

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**Abstract: Barriers to mitigating emissions from agriculture: Analysis of mitigation options, related barriers and recommendations for action**

On the basis of a literature review, this paper outlines the main mitigation options for agricultural activities and the broader food system on the supply and the demand side. Economic, policy/legal barriers, technical barriers, socio-cultural barriers, institutional barriers as well as biophysical or environmental barriers exist that hinder the implementation of these options. Such barriers operate at farm level, at national level, at the international level as well as at consumer level. The identified barriers are clustered and recommendations are developed to overcome them, including capacity building and education, participatory approaches with farmers, setting economic incentives right, redirecting public support to focus on sustainable practices, reforming agricultural subsidies, stricter regulations, improved tenure security, coherent policy signals, addressing policies and trade structures at international level and market regulations for fairer prices to producers. However, suitable approaches for the development of food systems need to be context-specific as agricultural systems as well as barriers obstructing the implementation of mitigation approaches are highly diverse and specific to local circumstances. Including mitigation targets related to agriculture in countries' NDCs provides an opportunity to raise ambition to tackle emissions related to food systems.

**Kurzbeschreibung: Hemmnisse zur Minderung der Emissionen aus der Landwirtschaft: Analyse von Minderungsoptionen, Hemmnisse für deren Umsetzung und Handlungsempfehlungen**

Auf der Grundlage einer Literaturrecherche werden in diesem Papier die wichtigsten Minderungsoptionen für die Landwirtschaft und das Nahrungsmittelsystem im weiteren Sinne auf der Angebots- und Nachfrageseite skizziert. Es gibt wirtschaftliche, politische/rechtliche, technische, soziokulturelle, institutionelle sowie biophysikalische und ökologische Hemmnisse, die die Umsetzung dieser Optionen behindern. Solche Hemmnisse bestehen auf der Ebene der landwirtschaftlichen Betriebe, auf nationaler und internationaler Ebene sowie auf der Ebene der Verbraucher*innen. Die ermittelten Hindernisse werden gebündelt und Empfehlungen zu ihrer Überwindung entwickelt, darunter Kapazitätsaufbau und Bildung, partizipatorische Ansätze mit Landwirt*innen, die richtige Setzung wirtschaftlicher Anreize, die Neuausrichtung der öffentlichen Unterstützung auf nachhaltige Praktiken, die Reformierung von Agrarsubventionen, strengere Vorschriften für den Sektor, mehr Sicherheit für Pacht- und Landnutzungsverträge, kohärente politische Signale, die Veränderung von Handelsstrukturen auf internationaler Ebene und Marktregelungen für gerechtere Preise für Erzeuger*innen. Geeignete Ansätze für die Entwicklung von Lebensmittelsystemen müssen kontextspezifisch sein, da die landwirtschaftlichen Systeme sowie die Hindernisse, die der Umsetzung von Minderungsoptionen im Wege stehen, sehr unterschiedlich und spezifisch für die lokalen Gegebenheiten sind. Die Aufnahme von Minderungszielen für die Landwirtschaft in die NDCs der Länder bietet die Möglichkeit, das Ambitionsniveau dieser Ziele zu erhöhen und mehr Anstrengungen zu verfolgen, die Emissionen im Zusammenhang mit unseren Lebensmittelsystemen zu reduzieren.

# Table of content

## List of figures

## List of abbreviations

| | |
|---|---|
| **AFOLU** | Agriculture, Forestry and Other Land Use |
| **AWD** | Alternate wetting and drying |
| **BSM** | Brazilian Soy Moratorium |
| **CBD** | Convention on Biological Diversity |
| **CCS** | Carbon capture and storage |
| **$CH_4$** | Methane |
| **$CO_2$** | Carbon dioxide |
| **COP** | Conference of the Parties |
| **FAO** | Food and Agriculture Organization |
| **FAOSTAT** | Food and Agriculture Organization Statistics |
| **FBO** | Farmer-based Organisation |
| **GDP** | Gross Domestic Product |
| **GHG** | Greenhouse gas |
| **Gt** | Giga tonne |
| **GWP** | Global warming potential |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LDC** | Least developed countries |
| **MRV** | Measurement, reporting and verification |
| **Mt** | Mega tonne |
| **N** | Nitrogen |
| **NbS** | Nature-based Solutions |
| **NDC** | Nationally Determined Contributions (in Paris Agreement) |
| **$N_2O$** | Nitrous oxide (laughing gas) |
| **$NO_2$** | Nitrogen dioxide |
| **NUE** | Nitrogen use efficiency |
| **$O_3$** | Ozone |
| **PJ** | Petajoule (energy measuring unit) |
| **PtG** | Power-to-Gas (any power-based gaseous fuels) |
| **PtL** | Power-to-Liquid (any power-based liquid fuels) |
| **R&D** | Research and development |
| **SDG** | Sustainable Development Goals |
| **SOC** | Soil organic carbon |
| **UNEP** | UN Environment Programme |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **USD** | US-Dollar |
| **VRNA** | Variable Rate Nutrient Application |
| **WTO** | World Trade Organization |

## Summary

Global warming is threatening our ecosystems and livelihoods. Reducing greenhouse gas emissions is a prerequisite to limit climate change and keeping our planet liveable. Food systems are the basis of our survival, but they are also part of the problem. The IPCC Special Report on Climate Change and Land Use estimates that a fifth to a third (21-37%) of global GHG emissions are attributable to our food systems: 9-14% is caused by crop production and livestock on farms, 5-14% by land use, and 5-10% from the food production value chain (IPCC 2019b, p. 58). In addition to being a source of greenhouse gases, the intensification of agriculture and the trend towards large-scale monocultures are major drivers of biodiversity loss and pressures on water resources. The pressure on ecosystems is increased particularly by the high and increasing consumption of animal products. Without a shift to diets that are predominantly plant-based and the implementation of further mitigation measures it will be impossible to meet the goals of the Paris Agreement and to keep the environmental effects of the food system within planetary boundaries (Clark et al. 2020; Willett et al. 2019; Springmann et al. 2018).

At the same time, the agricultural sector is responsible for providing sufficient, nutrient-rich food for a growing world population and thus plays a key role in achieving the Global Sustainable Development Goals (SDGs). Agriculture provides the economic livelihood for many people, especially in countries of the global South. An increase in agricultural productivity correlating with economic growth in the agricultural sector has a great potential for poverty alleviation. Yet, the agricultural sector is suffering the impacts of global warming, with far-reaching ecological, economic and social consequences. Making the agricultural system more sustainable involves two key priorities: preserving the environment and providing safe and healthy food for all.

In this report, we analyse a diverse range of mitigation options to make agriculture and the broader global food system more sustainable. For the agricultural sector, a technical mitigation potential of up to 9.6 Gt $CO_2$e/year on the supply side from crop and livestock activities and agroforestry and up to 8.0 Gt $CO_2$e/year on the demand side from dietary changes by 2050 has been identified. The economic mitigation potential is estimated at up to 4.0 Gt $CO_2$e/year from crop and livestock activities on the supply side by 2030 and up to 3.4 Gt $CO_2$e/year on the demand side by 2050 at prices of 20-100 USD $tCO_2$ (IPCC 2019c). Yet, barriers at the institutional, political, financial, socio-cultural, technical, or biophysical levels obstruct their implementation.

On the basis of a literature review, this paper outlines the main mitigation options for agricultural activities and the broader food system on the supply and the demand side as well as barriers for implementing these options. The identified barriers are clustered and recommendations are developed to overcome them. However, suitable approaches for the development of food systems need to be context-specific as agricultural systems as well as barriers obstructing the implementation of mitigation approaches are highly diverse and specific to local circumstances.

#### Supply side measures

Globally, the three main emission sources in the agricultural sector at the farm level are enteric fermentation, manure on pasturelands and the use of synthetic fertilisers, jointly accounting for over 65% of emissions in the sector (Thissen 2020 on the basis of FAO 2020a). The main mitigation measures and related barriers on the supply side include:

- **Changing the intensity of cultivation**: In order to reduce emissions from agriculture, the intensity of agricultural production needs to be considered. The extensification of crop

production can contribute to tackling emissions from agriculture and making production more environmentally sustainable. It can be an appropriate strategy in affluent regions if combined with adjusted diets that reduce global land demand and if environmental costs are reflected in food prices (van Grinsven et al. 2015). Extensifying agricultural production can reduce the amount of food produced or imply changes to the crops that are produced. In smallholder contexts in the global South, sustainable agricultural practices may therefore imply a "sustainable intensification" of agriculture. Concrete approaches/options for sustainable cultivation include (i) increasing the crop variety in order to conserve nutrients in the soil which is often referred to as "**conservation agriculture**" (Vanlauwe et al. 2014; Minasny et al. 2017; Oberč and Arroyo Schnell 2020); (ii) **agroforestry** to enhance yields from staple food crops, increase biodiversity, and enhance carbon sequestration while at the same time enhancing farmer livelihoods and resilience of soils; (iii) **increasing fallow land** or even afforest cropland if sufficient cropland is available ; (iv) **combined crop-livestock systems** allowing for optimal nutrient recycling and integrated nutrient management, reducing the need for chemical fertilisers (Oberč and Arroyo Schnell 2020); (v) **extensive grassland use** through rotational farming systems to reduce greenhouse gas emissions of livestock, enable healthy grasslands and increase animal welfare (Pretty and Bharucha 2014); (vi) **the integrated management of nutrients** forms through e.g. closed nutrient cycles (IUCN 2020); and (vii) **changing conventional agriculture to organic agriculture**.

- **Improved management of nitrogen fertilisers**: The AFOLU sector is the primary anthropogenic source of $N_2O$, which is mainly attributed to the application of nitrogen as soil fertiliser. However, around 50% of the nitrogen applied to agricultural land is not absorbed by crops (WRI 2018 p.48). In regions where application rates are high and exceed crop demands for parts of the growing season, decreasing or optimising the use of nitrogen fertiliser would have large effects on emission reductions (IPCC 2019b p.46). **Better management of fertilisers, increasing the nitrogen use efficiency rate, precision farming tools, substituting synthetic fertiliser for organic fertilisers, such as compost or manure, and incorporating nitrification inhibitors into fertiliser** are additional nitrogen management measures that can contribute to emission reductions. At the same time, reducing the use of fertiliser provides further benefits to the ecosystem as well as to human health. Nitrogen fertilisers are responsible for meeting half of the world's food demand (Erisman et al. 2008), so it is crucial for fertiliser use to be reduced without compromising crop yields.

- **Improved management of livestock manure**: Overall, manure from livestock accounts for roughly 25% of direct agricultural GHG emissions (Climate Focus; CEA 2014). The type of livestock production system affects the extent of manure left on the pasture versus the extent that is managed. Measures to reduce the emissions from livestock manure primarily consist of **best management practices for storage or for application on soils**. **Manipulating diets** can improve nitrogen utilisation by animals and reduce nitrogen excretion rates from manure (Samer 2015; Sajeev et al. 2018). Incorporating techniques such as reduced **storage time, covering the manure, and avoiding straw/hay bedding** can greatly reduce emissions from stored manure (Climate Focus; CEA 2014). **Digesters** can convert manure into methane for energy use. **Manure can also be recycled and used as compost**, or partially substitute synthetic fertiliser, provided it is combined with good practices for its application. **Integrated crop-livestock farming systems** are one example of how manure application can enhance agricultural productivity and reduce the use of mineral fertilisers (Reddy 2016).

- **Reduced emissions from livestock**: The livestock sector has major implications for natural resource consumption and livelihoods, and is responsible for approximately 16.5% of anthropogenic GHG emissions (Twine 2021). **Improved grazing land management, breeding optimisation, health monitoring and disease prevention as well as higher-quality feed have high potentials for mitigation** (FAO 2013a). Reducing the GHG emissions intensity per unit of livestock via these measures can support absolute emissions reductions, as long as total livestock production is limited (ibid). It is important to note that measures that improve livestock productivity, while reducing emissions intensity, are generally associated with higher absolute emission levels due to the increased performance of livestock. These measures would only result in a decrease of absolute emissions if **animal numbers were reduced** in conjunction (FAO 2017).

- **Carbon storage in agricultural systems**: Terrestrial soils are estimated to store twice as much carbon as currently contained in the atmosphere (Ciais et al. 2013). To prevent carbon loss from soils, avoiding conversion and degradation of sound ecosystems is of highest priority. Measures to increase the soil organic carbon stocks of land that is already used for agricultural purposes include e.g. the **use of mineral and organic inputs, more residue retention, agroforestry, reducing tillage and optimising crop rotation**. **Growing perennial or cover crops** are another way of increasing carbon stored in soils. To improve crop rotations, crops from different categories should be combined (primary and secondary cereals, grain legumes, temporary fodders, and to a lesser extent oilseeds, vegetables and root crops). In nutrient-deficient systems, **additional external fertiliser** can be used to increase carbon stored in soils. **In grasslands, optimal density of stocking and grazing** can increase soil carbon sequestration (Paustian et al. 2016). Furthermore, the addition of exogenous carbon inputs such as composts or biochar is discussed as a measure to increase soil carbon stocks. The mitigation effect of exogenous carbon inputs needs to be assessed in the context of a broader life-cycle assessment though. Increasing the carbon stored in soils implies multiple other environmental and social benefits.

- **Reduction of greenhouse gas emissions from rice cultivation**: Global anthropogenic $CH_4$ emissions from rice cultivation between 2008 and 2017 were 25-37 Mt/yr (0.7–1.03 Gt $CO_2e$). IPCC (2021) and estimates for 2019 place global $CH_4$ emissions from paddy rice at 24.08 Mt (0.67 Gt $CO_2e$) (FAO 2021a). **Changes in agricultural management practices** can lead to reduced $CH_4$ emissions from rice cultivation. The overall climate benefit, however, also depends on how $N_2O$ emissions are affected by these management changes, as often there are trade-offs between the mitigation of $CH_4$ emissions and $N_2O$ emissions (Yagi 2018; Kritee et al. 2018). The **water regime of rice**, especially the flooding pattern is a key lever to influence $CH_4$ emissions from rice fields (IPCC 2006), since continuously flooded rice fields generate more emissions than those exposed to aeration (IRRI 2007). **Aeration** can be achieved through periodic drainage of the rice field, which can be carried out in the middle of the growing season, a practice known as **mid-season drainage**, or several times during the growing season, also known as **alternate wetting and drying (AWD).** Another alternative water regime is to **replace flooding with controlled or intermittent irrigation**, which can lead to increased $N_2O$ emissions, but still has a positive overall effect on GHG emissions (Hussain et al. 2014). Additional options to reduce $CH_4$ emissions from rice cultivation include **improved rice straw management, improved fertiliser management, changes in planting methods as well as improving rice varieties**.

- **Burning practices**: Crop residue burning is the practice of burning post-harvest crop stubble from grains to minimise the time between harvesting and sowing new seeds. It increases black carbon pollution (with adverse health effects) and GHG emissions, harms soil fertility, and carries the risk of uncontrolled fires. Burning practices continue to be common in parts of India, China, and Southeast Asia since rapid intensification has imposed economic and practical limitations to good residue management. Crop residues from rice produced in the tropics can be effectively utilised as mulch, compost, biochar, or used for bioenergy production with notable benefits (Bhuvaneshwari et al. 2019).

#### Demand-side measures

To reduce emissions from agriculture, and besides changing agricultural practices at the supply side, food-related emissions need to be addressed at the demand side as well. Demand side measures to change production and consumption patterns can not only reduce emissions, but also reduce stress on land use and allow for restoration of natural ecosystems and forest due to less land needed for agricultural use (UBA 2020). Three key approaches for reducing emissions from agriculture at the demand side include:

- **Reducing food waste and losses**: FAO (2019a) defines food loss and waste "as the decrease in quantity or quality of food along the food supply chain". Estimates for the share of total food produced that is lost or wasted range from to 25-30% (IPCC 2019a). The loss of edible food as well as food waste by retailers and consumers entail higher levels of agricultural production, which in turn increases GHG emissions and overall pressure on natural resources (Hiç et al. 2016). The reasons for food loss and waste differ substantially in developed and developing countries, and across regions as well as commodity groups. They relate to all stages of the food chain and include pests, natural disasters, weather events, poor agricultural practices, inadequate storage facilities, poor handling practices during processing and transport, market conditions, package design by companies, handling of expiry dates, consumer preferences, and individual behaviour (IPCC 2019b; FAO 2019; HLPE 2014; Poore und Nemecek 2018; WWF 2021). To tackle food waste in different global regions, **technical options** for reduction of food loss and waste include improved harvesting techniques, improved on-farm storage at farm level and improved food transport and distribution, better infrastructure for storing food, shortening supply chains (new ways of selling, e.g. direct sales) or strengthening food producers' position in the supply chain, and improving packaging during the supply chain (IPCC 2019b, pp. 58–60; HLPE 2014). Also, **behavioural changes** are needed to reduce food waste, such as acceptance of less-than-perfect fruits and vegetables, higher sensitivity for food waste impacts on a global scale, and improved management of buying and using food at home (Rosenzweig et al. 2020).

- **Changing dietary habits**: Changing dietary habits offers a lot of potential for tackling the question of food security and reducing GHG emissions. However, promoting changes to dietary habits is politically sensitive as it affects people's freedom of choice and established habits that may be deeply rooted in social and cultural traditions that are difficult to break with. Sustainably changing dietary habits involves a **general reduction of per capita consumption of calories (in regions with overconsumption) to healthy levels as well as adopting a plant-rich diet**. **Excluding animal products** from the diet can make a huge difference, whereas reducing beef consumption plays a pivotal role (Clark et al. 2020; WRI 2016). Shifting to alternative, healthier diets that include sustainability considerations, i.e. less consumption of meat and dairy products, referred to by FAO (2020b), could help to reduce health *and* climate change costs by 2030. Additionally, more than 40% of global crop calories are used as livestock feed today (Pradhan et al. 2013). With radical changes to current dietary choices, the current production of crops would be sufficient to provide enough food for a projected global population of 9.7 billion in 2050 (Berners-Lee et al.

2018). Shifting diets can therefore be considered as a strong tool to ensure food security for a global population (UBA 2021).

- **Reducing deforestation to create arable land and grassland**: Eliminating net deforestation in the next decade is a key component of emissions pathways consistent with limiting global warming to 1.5°C. Around 60% of tropical deforestation is driven by expansion of agricultural land for cropland, pastures and plantations, with cattle and oilseed as largest contributors (Pendrill et al. 2019). If demand for these products is reduced, less land is needed to grow animal feed and energy crops which in turn reduces the pressure on ecosystems. Reducing further agricultural expansion and its associated deforestation provides a number of environmental and social co-benefits such as preservation of natural habitats and reducing biodiversity loss. Reducing deforestation emissions from agricultural expansion can be broadly addressed in two ways; (1) **measures that directly target deforestation and preserve forested areas**, and (2) **measures that reduce the demand for new agricultural land and its expansion into forests**.

#### Barriers for ambitious mitigation in the agricultural sector

The IPCC Special Report on Climate Change and Land (IPCC 2019b) differentiates six types of barriers which obstruct mitigation action in the agricultural sector: **Economic barriers** imply that market structures and market actors work against more ambitious climate protection in agriculture through e.g. low world market prices, established infrastructure, lack of sales markets for climate-friendly food etc. **Policy/legal barriers** include existing laws and regulations, financial incentives or resources, and the design of support instruments at national, regional, and international levels, some of which are counterproductive to ambitious climate action in agriculture. **Technical barriers** relate to lacking knowledge or the availability of appropriate technologies. **Socio-cultural barriers** result from behavioural and lifestyle patterns or values underlying our diets and attitudes towards food. **Institutional barriers** due to different responsibilities and division of competencies may also complicate reform processes. **Biophysical or environmental barriers** include factors that reduce fertile land use areas or food production, such as salinisation, temperature rise, or extreme weather events like floods or drought.

The barriers identified for the different mitigation options can be clustered according to the relevant governance level for taking action. It must be noted that the relevance of specific barriers strongly depends on local circumstances. At the most basic level, biophysical conditions define the framework for appropriate mitigation options. These include climate conditions and soil structure, but also farm size and the type of agricultural activities that are prevalent. The assessment, planning and implementation of national climate policies in the agricultural sector as well as approaches for overcoming existing barriers will therefore need to be context-specific (OECD 2017; IPCC 2019a).

A number of the identified barriers **<u>operate at the farm level</u>**:

- Economic barriers
  - The **lack of specific economic benefits** to farmers act as a barrier to the implementation of mitigation measures at farm level. If change implies **high adoption/transaction costs** at the farm level, particularly with regard to capital costs, this will inhibit farmers from changing their practices (OECD 2017; Smith et al. 2007a; Mills et al. 2020). **Lack of access to credits** for investing in infrastructure, machinery and equipment reinforces this barrier (OECD 2017; Wageningen University 2014). Lacking financial resources to invest in better harvesting and storage technologies have

also been identified as a barrier to reducing food loss and waste at the farm level (FAO 2019a). **Uncertainty about the impact of changing agricultural practices** on farm business is a further barrier to change (Kragt et al. 2017).

- Such barriers are reinforced by **structural factors, such as farmers' age or farm size**, that will impact the likelihood of implementing innovations (OECD 2017; Mills et al. 2020; Knowler and Bradshaw 2007).

- Policy/legal barriers:
  - A farmer's decision to adopt climate-friendly measures depends on the **regulation of land tenure**, with long-term land tenure positively affecting the willingness to apply climate friendly measures such as sustainable soil management (OECD 2017; Aryal et al. 2020; Congressional Research Service 2020).
  - Lack of **institutional support, advice or information** available to the farm level was also found to act as a barrier to the adoption of more sustainable farm management practices (Mills et al. 2020).
- Technical barriers
  - The **lack of technology** or capacity of small-scale farmers can also be a barrier to changing agricultural practices, e.g. maintaining unsustainable burning practices of agricultural waste in India, China and Southeast Asia (Bhuvaneshwari et al. 2019) or implementing agroforestry practices.
- Socio-cultural barriers
  - Further factors at farm level relate to **personal attitudes, traditions and practices** which will impact the acceptance of mitigation measures (OECD 2017; Mills et al. 2020). Risk aversion has also shown to be a significant social barrier to reducing fertiliser overapplication (Robertson and Vitousek 2009). Additionally, gender roles might act as a social barrier to access to information (Aryal et al. 2020). Particularly in the context of smallholder farming, the social and cultural role of livestock rearing, as well as the dependency of livelihoods on livestock, are strong arguments against reducing the emissions from livestock by reducing the number of animals (Herrero et al. 2016; Thornton 2010).
  - Additionally, **lack of awareness** of climate change and its consequences and a **lack of knowledge** about mitigation measures and their benefits and how to implement them has been found to prevent farmers from investing in GHG mitigation measures in Southeast Asia (Aryal et al. 2020). Studies from India and the US have shown that farmers lack awareness of the relationship between fertiliser application and climate change, for example, and receive advice for how to apply fertilisers from economic actors with vested interests (Stuart et al. 2013; Pandey and Diwan 2018).
- Biophysical/environmental barriers
  - The **reversibility of emission reductions** or carbon sequestration in the agricultural sector can act as a biophysical barrier to the implementation of mitigation measures, e.g. by inhibiting farmers to implement climate-friendly cultivation practices because the outcomes might not be permanent (Aryal et al. 2020).

**At the national scale**, different types of barriers can obstruct enhancing mitigation in the agricultural sector:

- Economic barriers
  - Firstly, resistance against mitigation options emerges from perceived **potential negative effects on production**, particularly in countries where agriculture is an important sector for the economy (OECD 2017). If deforestation brings economic advantages, political will may be weak to implement stricter regulations (Kalaba 2016). **Economic objectives to increase agricultural output** might also act as barriers against more sustainable forms of agricultural production.
  - In regions where **food security** is the predominant policy objective, the intent to increase production levels might even prevent the protection of carbon-rich soils that are not used for agricultural purposes yet (Minasny et al. 2017).
  - Secondly, **cooperation with industries** can obstruct changes in crop cultivation, e.g. if contracts have been concluded that focus on yields or if relations with processing factories are long-established (OECD 2017).
- Policy/legal barriers
  - **Policies to support production, such as input subsidies or tax exemptions**, may pose obstacles to climate-friendly agricultural practices (OECD 2017), as they imply that more revenues can be generated with conventional, intensive, monocrop cultivation systems (Oberč and Arroyo Schnell 2020). For example, crop subsidy payments based on the extent of production perversely promote fertiliser overapplication (Robertson and Vitousek 2009). Likewise, existing financial incentives often target anaerobic digester construction rather than the value of the output, which does not stimulate farmers to improve their manure management. Replacing synthetic fertiliser with manure is disincentivised by existing fertiliser subsidies (Tan et al. 2021). The largest share of direct production subsidies provided to farmers at global scale goes to the largest farms that are better equipped to handle price and income fluctuations by themselves than small-scale farmers (Searchinger 2020). Only a limited portion of this support is used to drive climate mitigation, albeit environmental conditionality for agricultural support has become more stringent in recent years (World Bank 2020).
  - **Property rights** might counteract mitigation action in the agricultural sector as well. If there is no clear ownership by a single party defined, this might inhibit the implementation of management changes (Smith et al. 2007a).
- Technical barriers
  - **MRV systems** defining the way in which emissions are reported and accounted for may provide barriers at the national level. Many mitigation practices are not captured in the inventory accounting if countries are not applying complex methodologies (Tier 3) of the IPCC inventory guidelines. This reduces the recognition that governments can gain from implementing mitigation policies in the agricultural sector (OECD 2019b). Other environmental benefits are not taken into consideration in this accounting at all. Furthermore, data on emissions related to soil carbon stock changes resulting from land cover, land-use change or soil use in production processes is missing (OECD 2017; Bispo et al. 2017).

- Regarding food waste and loss, the lack of solid data presents a major barrier for successful policymaking (FAO 2019a).

► Socio-cultural barriers

- Additionally, a **lack of education and awareness** on the negative effects of agriculture on climate change can act as a barrier against more climate-friendly practices at the level of policymakers (OECD 2017).

► Institutional barriers

- The **absence of a well-designed climate policy** that includes the agricultural sector can act as a barrier to mitigation practices in that no incentives for these practices are available (OECD 2017). This can result from a **lack of a goal or vision of sustainable agriculture** that prevents coherent policy incentives for sustainable practices (Oberč and Arroyo Schnell 2020). Moreover, a lack of coordination between different governance levels or ministries hinder the implementation of ambitious mitigation action (Aryal et al. 2020). For governments in the global South, weak enforcement capacities and understaffed and underfunded environmental authorities pose barriers to effective regulation of deforestation for agricultural purposes (Furumo and Lambin 2020).

**Barriers at the international level** arise from the following aspects:

► Economic barriers

- Economic competition between countries posing barriers to implementing mitigation policies: the possibility of **carbon leakage** to other countries as a result of stricter mitigation policies in one country which will put this country at disadvantage in the competition with others (OECD 2017). Particularly introducing sectoral policies for livestock emissions reduction only in the global North would imply that two thirds of the emissions reductions would be offset by increased methane emissions in the global South due to shifting from domestic production to imported livestock products (Key and Tallard 2012).

- The global consolidation of the food industry has created large-scale actors with global influence on dietary habits. As a result, the food industry is driven by **vested economic interests** that are challenging to address politically (GRAIN; IATP 2018).

- As agricultural trade is globalised, there are **long supply chains** for agricultural products that act as indirect drivers of deforestation (e.g. the demand for palm oil products). With many actors involved, regulation as well as monitoring of deforestation at global level is challenging.

► Policy/legal barriers

- **Insufficient financial support** may also pose obstacles to adopting climate-friendly agricultural practices (Aryal et al. 2020).

- Low world market prices and dependency of smallholder farmers on **asymmetric trade structures** are a major barrier to tackling food loss and waste as they may imply last minute cancellations which mean that farmers cannot afford to harvest surplus food (WWF 2021). Power imbalances between farmers and retailers are structural drivers that keep farmers' incomes supressed and maintain the status quo (WWF 2021).

- Mitigation measures in the agricultural sector might conflict with **international trade law**, e.g. if support provided to national producers reducing GHG emissions in their production at the same time contributes to promoting increased exports or replace imports; if climate-‘unfriendly’ products and production methods are taxed at the border or if labelling to inform consumers is not based on internationally agreed standards (Häberli 2018).
- **Free trade agreements** can induce governments to shift subsidies so that they are less market-distorting but this was not found to have significant effects on global emissions (Searchinger 2020).

► Technical barriers

- The **lack of common metrics and indicators** acts as another barrier to implementing mitigation action in the agricultural sector. If quantitative evidence of the benefits of a measure is not available, it will be difficult to convince famers, consumers or policymakers to support change (IUCN 2020).
- Also clear scientific targets for achieving healthy diets are missing, thus obstructing a shift to a sustainable global food system (Willett et al. 2019).
- Due to the **lack of standards for data collection**, no commonly agreed evaluation method, and different definitions there is a huge barrier to identify the causes and the extent of food loss and waste (HLPE 2014).
- With regard to halting deforestation, **challenges to monitor and control, meaning a lack of transparency**, pose a barrier to effective international action. This applies both to what is actually happening on the ground in terms of trees cut down, and also to supply chains with multiple actors involved that may be spread internationally, adding to the challenge of holding someone accountable (NewClimate Institute 2021).

**Barriers at the consumer level** mainly relate so socio-cultural aspects such as food culture and tradition. Changing diets interacts with peoples’ **subjective freedom of choice** as well as with **social and cultural habits** and is therefore politically sensitive. Additionally, the benefits of sustainable diets have so far not been communicated properly and shifts to such diets have appeared disruptive to consumers (WRI 2016). A barrier against the use of insect protein in diets is the low acceptance of insect-based food in Western societies (Wendin and Nyberg 2021). Additionally, regulation is lacking to bring insects into food supply systems in Western countries (Dobermann et al. 2017). Furthermore, **eating habits and high standards** for the shape and appearance of food, as well as expectations of an unlimited choice of all products at any time of the year, drive food loss and waste at international level.

#### Recommendations for action

The transformation that is required to change the global food system requires engagement from actors at all levels.

Ultimately, change in agricultural production will be implemented by farmers, farm managers and communities who manage trees, crops, livestock, fields and landscapes. **At (small-scale) farm level, capacity-building is needed in order to disseminate information to local actors and enhance knowledge on the benefits from changing agricultural practices**. For example, to address food loss and waste, agronomic training and education for farmers (as well as other actors along the food chain) is necessary to change practices (HLPE 2014).

In providing training and financial support as incentives to farmers to change agricultural practices, **participatory approaches** appreciating local knowledge and engaging local stakeholders can be beneficial. In that context, knowledge networks play a crucial role. Farmer-to-farmer learning can help to understand the long-term benefits of sustainable agricultural practices (Aryal et al. 2020)

Additionally, **farmers need financial support and the provision of the right economic incentives** in order to change agricultural practices. Payments to make up for perceived financial risks can support such changes and incentives should be based on delivering ecosystem services. Microfinance initiatives providing financial and technological support can also help to address food loss and waste, e.g. by supporting farmers in taking up innovations, adjusting crops to minimise food loss and increasing access to cooling (WWF 2021).

**At the national and subnational level**, laws and regulations need to be set in the right way to provide incentives to shift production to more sustainable alternatives. Particularly, on a governmental level, **public support needs to be redirected to focus on sustainable practices** (World Bank 2020; Climate Focus; CEA 2014; FAO and UNDP 2021). Financial incentives should be based on ecosystem services instead of being tied to the size of farms or the yield only (Robertson and Vitousek 2009). Direct payments should also be linked to the condition of not clearing new land unless inevitable to guarantee food security (World Bank 2020).

**Agricultural subsidies need to be reformed.** For high-income countries, harmful support needs to be abolished. Support should not be coupled to production volumes and incentives should particularly be provided for the production of nutritious food for healthy diets. In middle-income countries, subsidies should be decoupled from production or inputs as well. Negative effects for low-income groups should be mitigated by appropriate compensatory measures. In low-income countries, additionally, a freer trade and market environment helps to enable higher income for farmers and make the agricultural business more sustainable. Consumer subsidies accompanied by well-designed social protection schemes could support healthy diets in poorer countries. In decoupling payments from production, specific commodities or yields, smallholder farmers can be better targeted as well. Repurposing agricultural support needs to be accompanied by communicating that the shifts are not about reducing support for farmers but re-allocating it in a way that entails greater benefits for society as a whole (FAO and UNDP 2021).

**Targeted support and linking domestic credit lines to policies and best practices** can support producers in moving towards sustainable agricultural production and forest use (Global Canopy Programme 2015) as well as to reduce food waste. To address (perceived) economic risks, public and/or private support should be made available to the transitioning period in which more sustainable practices are implemented (e.g. growing trees in agroforestry systems) (IUCN 2020). Where possible, support should also promote the retirement and restoration of land that is not urgently needed for agricultural purposes. Systems of graduated payments rewarding farmers for increasingly better performance have shown to be more prone to promote climate change mitigation than setting minimum environmental standards. Also, support should enhance innovation by e.g. promoting new technologies that have the potential to become self-sustaining if used more widely (World Bank 2020). Financial incentives should be tied to **environmental requirements** that need to be high. Market-based instruments are often mentioned in the literature as a means to incentivise further mitigation action in the agricultural sector (e.g. Smith et al. 2007b; Minasny et al. 2017). However, emission reduction projects that sequester carbon typically cannot guarantee permanent storage of carbon (over a period of hundreds of years, to millennia). This, amongst other risks to their environmental integrity (UBA 2022), undermines their suitability to represent a genuine option for offsetting emissions occurring elsewhere.

Financial support to shift to more sustainable practices should be aligned with **new, stricter regulations**, e.g. regarding manure management or carbon taxes to reduce GHG emissions from livestock production or fertiliser use (Paustian et al. 2016; Minasny et al. 2017). [1] When designing such incentives, it needs to be ensured that they do not increase overall production output (where this is not needed to ensure food security) or shift emissions to other countries (Thornton et al. 2007). Taxes should send the appropriate signals on the ecological footprint of products to consumers in order to reduce the demand for land-intensive products, particularly meat (Boerema et al. 2016; Sisnowski et al. 2017). Procurement policies provide an additional lever to promote healthy diets implying more sustainable agricultural practices in workplaces, schools and other venues where meals are publicly provided (Willett et al. 2019). **Reforms to improve tenure security** can reduce deforestation and unsustainable agricultural practices, albeit being a sensitive issue (Angelsen 2010; UBA 2021).

Additionally, it is crucial to **send coherent policy signals to the agricultural sector** (OECD 2019a). Climate and environmental effects should be considered in every policymaking that affects agricultural systems. Engagement of subnational food system actors such as farmers, food manufacturers and retailers can help to create strong national frameworks for implementing measures to mitigate emissions from the broader food system (Global Alliance for the Future of Food 2022). Policies are needed that regulate sectoral emissions for the whole land use sector in order to prevent the expansion of production due to improvements in efficiency or increased profits, especially regarding livestock (FAO 2013a). Better coordination between health, agriculture, water and environment departments is also needed to ensure coherence among policies affecting sustainable diets (WRI 2016; FAO and UNDP 2021).

**Monitoring and evaluation of the measures taken** is necessary in order to drive environmental progress and improvements of policy over time (World Bank 2020), particularly regarding measures to address food loss and waste as well as to address deforestation (Global Canopy Programme 2015).

**To address barriers at the international level, multilateral initiatives and summits at the global level need to set the appropriate global framework** for achieving a more sustainable food system through targets, standards and providing a forum for continuous exchange. The UN Food Systems Summits, the Conferences of the Parties (COPs) under the Convention on Biological Diversity (CBD) as well as the UNFCCC bring the global community together to do so (FAO and UNDP 2021).

Furthermore, at the international level, **policies and trade structures need to change** in order to set the right incentives for more sustainable agricultural production. Adjustments to WTO rules might be necessary in order to avoid conflicts between mitigation policies and trade law (Häberli 2018). Taxes have been found to have greater impact on consumption if they are applied in broader regions instead of single countries, if the substitutes are taxed as well and if the taxes are sufficiently high (WRI 2016). The WTO can play a central role in coordinating members to take concerted efforts to reduce distorting agricultural measures while at the same time supporting the transition to sustainable food systems.

Farmers need to be paid **fairer prices** in order to be able to improve harvesting and field management techniques. High levels of subsidies in some countries can depress world prices

[1] E.g. the US Department of Agriculture programmes include mitigation as a conservation goal; provisons in the EU Common Agricultural Policy link subsidy payments to 'cross-compliance' measures that include maintaining the soil organic carbon content (Louwagie et al. 2011).

and thus reduce incomes for other agricultural exporters and local producers. Cartels related to food production and trade as well as financial speculation on food have strong negative effects on populations in low-income countries that depend on global markets (IPCC 2019c). Market regulations and fair trade laws promoting contractual arrangements to share risks more equitably between producers and retailers are therefore necessary, e.g. to empower farmers to address food waste at farm level (WWF 2021).

Particularly to address agricultural expansion and resulting deforestation, a context-specific systems perspective that addresses drivers at all elements of the supply chain is necessary. Holding all actors responsible across the supply chain would need **international regulation** efforts to reduce deforestation (European Parliament 2020; Hughes and Terazono 2020). Developing multilateral public-private partnerships would be one approach to address deforestation (Furumo and Lambin 2020).

Additionally, **more work is needed by the research community to support a sustainable transformation of agriculture**. Firstly, the setting of common definitions, metrics and indicators will help to measure the benefits of approaches to sustainable agriculture (Oberč and Arroyo Schnell 2020; Frison 2020). Also, the evidence base on the impacts of agricultural support (FAO and UNDP 2021) as well as on measuring the impacts of policies on soil health needs to be further developed (Bispo et al. 2017). Furthermore cooperation at international level will be necessary in order to develop standards and guidance for better MRV of emissions related to soils. The experiences on best practises for reducing food waste and losses could be exchanged on a regular and international basis among science and politics to reach global improvements and promote public interest and debate on the issue.

**At consumer level,** mostly socio-cultural as well as economic barriers play a role. **Education and knowledge as well as societal dialogue processes and guiding principles** are key drivers for overcoming such barriers. Meat analogues such as imitation meat (from plant products), cultured meat and insects may support the shift towards more sustainable diets. Advocacy and education is also necessary to promote knowledge on food loss and waste as an incentive to change behaviour. This needs to be supported by **expanding product specifications** to lower the standards for shape and appearance of food, especially fruits and vegetables, at governmental level (WWF 2021). Additionally, **date labelling policies** need to provide clear signals to consumers (HLPE 2014). Furthermore, **technical options could support behavioural changes by consumers**, such as better packaging or the development of "doggy bag" practices in restaurants (HLPE 2014). Food banking by non-governmental initiatives to distribute surplus food can also support efforts to reduce food loss and waste. Governments should provide tax-related incentives to support donations (HLPE 2014).

Generally, barriers at consumer level to adopting more sustainable, healthy diets are closely linked to broader questions of inequality. It is therefore necessary to make sustainable food more affordable to all consumers as well as to apply "nudging" approaches that direct consumers to make "better choices" (e.g. by providing sustainable choices as defaults or presenting healthier options more attractively) (Reisch et al. 2013). Improving social welfare in general will support efforts to promote a shift towards healthier diets.

To address the barriers described in this paper it is essential to involve actors across all governance levels and along the whole supply chain. As a priority, those barriers should be considered which have been identified with sufficiently robust evidence in the literature, are easiest to tackle, are most urgent to change practices with damaging effects to the climate, have largest savings potentials and can be supported by joint international efforts. As natural, social and economic conditions vary widely across geographies, any measures to enhance mitigation action in the agricultural sector needs to be carefully tailored to national or regional needs and circumstances.

To ensure food supply in the context of the consequences of Russia's war against Ukraine, it is essential to prevent price-pushing export restrictions by large agricultural countries and keep trade open (Rudloff and Götz 2022). At the same time, recent reactions by the EU as well as the US to suspend conservation programmes, postpone legislation on nature protection and regulation on pesticides risk to put further pressure on natural resources and biodiversity (Rudloff and Götz 2022; The Greens/EFA 2022). It is now more important than ever to pursue strategies to align food security with the fight against climate change and the erosion of biodiversity at global and national level to achieve a more sustainable food system for all in the future.

Including mitigation targets related to agriculture in countries' NDCs provides an opportunity to raise ambition to tackle emissions related to food systems. So far, NDCs often focus on food production aspects, leaving demand-side measures to promote dietary changes and tackling food waste aside. Enhancing the engagement of all relevant stakeholders in NDC development processes and aligning agricultural support and other policies with mitigation targets can help to use the NDC process to promote mitigation in the agricultural sector (Global Alliance for the Future of Food 2022).

The means to mitigate emissions from agriculture while at the same time promoting increased food security are there. To achieve a sustainable transformation of our food system, we need to rethink our approach and our attitude to agriculture instead of focusing only on technical solutions. Engagement from governments, companies, producers and consumers is required to do so, supported by an agenda set at the international level.

## Zusammenfassung

Die globale Erwärmung bedroht unsere Ökosysteme und Lebensgrundlagen. Um den Klimawandel zu begrenzen und unseren Planeten lebenswert zu erhalten, müssen die globalen Treibhausgasemissionen drastisch reduziert werden. Die Ernährungssysteme sind die Grundlage menschlichen Lebens, aber sie sind auch Teil des Problems. Der IPCC-Sonderbericht über Klimawandel und Landnutzung schätzt, dass ein Fünftel bis ein Drittel (21-37 %) der weltweiten Treibhausgasemissionen auf unsere Ernährungssysteme zurückzuführen sind: 9-14 % werden durch den Pflanzenbau und die Tierhaltung in landwirtschaftlichen Betrieben verursacht, 5-14 % durch die Landnutzung und 5-10 % durch die Wertschöpfungskette der Lebensmittelproduktion (IPCC 2019b, S. 58). Die Intensivierung der Landwirtschaft und der Trend zu großflächigen Monokulturen sind nicht nur eine Quelle von Treibhausgasen, sondern tragen auch zum Verlust der biologischen Vielfalt bei und gefährden verfügbare Wasserressourcen. Der Druck auf die Ökosysteme wird vor allem durch den hohen und zunehmenden Verbrauch von tierischen Produkten verstärkt. Ohne eine Umstellung auf eine überwiegend pflanzliche Ernährung und die Umsetzung weiterer Klimaschutzmaßnahmen wird es nicht möglich sein, die Ziele des Pariser Abkommens zu erreichen und die Umweltauswirkungen des Ernährungssystems innerhalb der planetarischen Grenzen zu halten (Clark et al. 2020; Willett et al. 2019; Springmann et al. 2018).

Gleichzeitig ist der Agrarsektor für die Bereitstellung ausreichender, nährstoffreicher Lebensmittel für eine wachsende Weltbevölkerung verantwortlich und spielt damit eine Schlüsselrolle bei der Erreichung der globalen Ziele für nachhaltige Entwicklung (SDGs). Die Landwirtschaft bildet die wirtschaftliche Grundlage für viele Menschen, insbesondere in den Ländern des globalen Südens. Eine Steigerung der landwirtschaftlichen Produktivität, die mit wirtschaftlichem Wachstum im Agrarsektor einhergeht, birgt ein großes Potenzial, um die globale Armut zu bekämpfen. Allerdings leidet der Agrarsektor unter den Auswirkungen der globalen Erwärmung, was weitreichende ökologische, wirtschaftliche und soziale Folgen hat. Um das Agrarsystem nachhaltiger zu gestalten, müssen zwei Schwerpunkte gesetzt werden: die Erhaltung der Umwelt und die Bereitstellung sicherer und gesunder Nahrungsmittel für alle.

In diesem Bericht analysieren wir eine Reihe von Optionen, um die Landwirtschaft und das globale Lebensmittelsystem im weiteren Sinne nachhaltiger zu gestalten. Für den Agrarsektor wurde ein technisches Minderungspotenzial von bis zu 9,6 Gt $CO_2$e/Jahr auf der Angebotsseite durch Ackerbau, Viehzucht und Agroforstwirtschaft und von bis zu 8,0 Gt $CO_2$e/Jahr auf der Nachfrageseite durch eine veränderte Ernährungsweise bis 2050 ermittelt. Das wirtschaftliche Minderungspotenzial wird auf bis zu 4,0 Gt $CO_2$e/Jahr durch pflanzliche und tierische Aktivitäten auf der Angebotsseite bis 2030 und bis zu 3,4 Gt $CO_2$e/Jahr auf der Nachfrageseite bis 2050 bei Preisen von 20-100 USD t$CO_2$ geschätzt (IPCC 2019c). Jedoch beeinträchtigen institutionelle, politische, finanzielle, soziokulturelle, technische und biophysikalische Hindernisse die Umsetzung dieser Optionen.

Auf der Grundlage einer Literaturrecherche werden in diesem Papier die wichtigsten Minderungsoptionen für landwirtschaftliche Aktivitäten und das Nahrungsmittelsystem im weiteren Sinne auf der Angebots- und Nachfrageseite sowie die Hindernisse für die Umsetzung dieser Optionen beschrieben. Die identifizierten Hindernisse werden gebündelt und Empfehlungen zu deren Überwindung entwickelt. Geeignete Ansätze für die Entwicklung von Lebensmittelsystemen müssen kontextspezifisch sein, da sowohl die landwirtschaftlichen Systeme als auch die Hindernisse, die der Umsetzung von Minderungsansätzen im Wege stehen, sehr unterschiedlich und spezifisch für die lokalen Gegebenheiten sind.

**Maßnahmen auf der Angebotsseite**

Weltweit sind die drei wichtigsten Emissionsquellen durch landwirtschaftliche Betriebe die enterische Fermentation, die Düngung von Weideflächen und der Einsatz synthetischer Düngemittel, die zusammen für mehr als 65 % der Emissionen in diesem Sektor verantwortlich sind (Thissen 2020 auf der Grundlage von FAO 2020a). Zu den wichtigsten Minderungsmaßnahmen und den damit verbundenen Hemmnissen auf der Angebotsseite gehören:

- **Änderung der Anbauintensität**: Um die Emissionen aus der Landwirtschaft zu reduzieren, muss die Intensität der landwirtschaftlichen Produktion berücksichtigt werden. Die Extensivierung von Anbaumethoden kann dazu beitragen, die Emissionen aus der Landwirtschaft zu verringern und die Produktion umweltverträglicher zu gestalten. Sie kann in wohlhabenden Regionen eine geeignete Strategie sein, wenn sie mit einer angepassten Ernährung kombiniert wird, die den globalen Landbedarf reduziert, und wenn sich die Umweltkosten in den Lebensmittelpreisen widerspiegeln (van Grinsven et al. 2015). Die Extensivierung der landwirtschaftlichen Produktion kann allerdings zu weniger produzierten Nahrungsmitteln oder anderen Feldfrüchten führen. Für die kleinbäuerliche Landwirtschaft im globalen Süden können nachhaltige landwirtschaftliche Praktiken daher eine "nachhaltige Intensivierung" der Landwirtschaft bedeuten. Die folgenden Optionen können die Intensität des Anbaus nachhaltiger gestalten: (i) die Erhöhung der Kulturpflanzenvielfalt, um Nährstoffe im Boden zu erhalten ("**konservierende Landwirtschaft**") (Vanlauwe et al. 2014; Minasny et al. 2017; Oberč und Arroyo Schnell 2020); (ii) **Agroforstwirtschaft**, um die Erträge von Grundnahrungsmitteln zu steigern, die biologische Vielfalt zu erhöhen, mehr Kohlenstoff im Boden zu binden, neue Einnahmequellen für Landwirt*innen zu generieren und den Boden widerstandsfähiger zu machen; (iii) **Flächen ungenutzt lassen** oder Ackerflächen aufforsten, sofern genügend Anbauflächen zur Verfügung stehen; (iv) **kombinierte Systeme aus Ackerbau und Viehzucht**, die ein optimales Nährstoffrecycling und ein integriertes Nährstoffmanagement ermöglichen, sodass weniger chemische Düngemittel benötigt werden (Oberč und Arroyo Schnell 2020); (v) **extensive Grünlandnutzung** durch rotierende Nutzung der Flächen, um die Treibhausgasemissionen der Viehzucht zu verringern, gesundes Grünland zu ermöglichen und das Wohlergehen der Tiere zu verbessern (Pretty und Bharucha 2014); (vi) **integriertes Nährstoffmanagement**, z. B. durch geschlossene Nährstoffkreisläufe (IUCN 2020); und (vii) **die Umstellung der konventionellen Landwirtschaft auf ökologischen Landbau**.

- **Verbessertes Management von Stickstoffdüngern**: Der AFOLU-Sektor ist die größte anthropogene $N_2O$-Quelle, was hauptsächlich auf die Ausbringung von Stickstoff als Bodendünger zurückzuführen ist. Rund 50 % des auf landwirtschaftliche Flächen ausgebrachten Stickstoffs wird jedoch nicht von den Pflanzen aufgenommen (WRI 2018, S. 48). In Regionen, in denen die Ausbringungsraten hoch sind und den Bedarf der Pflanzen während eines Teils der Vegetationsperiode übersteigen, könnten verringerte oder optimierte Mengen von Stickstoffdünger die Emissionen beträchtlich reduzieren (IPCC 2019b S. 46). **Der verbesserte Einsatz von Düngemitteln, höhere Stickstoffnutzungsraten, Präzisionslandwirtschaft, die Substitution von synthetischem Dünger durch organische Düngemittel wie Kompost oder Dung und die Beimischung von Nitrifikationshemmern zu Düngemitteln sind zusätzliche Maßnahmen zum Stickstoffmanagement, die zu Emissionsminderungen beitragen können.** Gleichzeitig bringt die Verringerung des Düngemitteleinsatzes weitere Vorteile für das Ökosystem und die menschliche Gesundheit mit sich. Stickstoffdünger sind für die

Deckung der Hälfte des weltweiten Nahrungsmittelbedarfs verantwortlich (Erisman et al. 2008), daher ist es von entscheidender Bedeutung, dass der Düngemitteleinsatz reduziert wird, ohne die Ernteerträge zu beeinträchtigen.

- **Besseres Management von Viehdung**: Insgesamt entfallen rund 25 % der direkten landwirtschaftlichen THG-Emissionen auf Dung aus der Viehhaltung (Climate Focus; CEA 2014). Die Art des Tierhaltungssystems beeinflusst die Menge an Dung, die auf der Weide bleibt. Die Emissionen von Viehdung können in erster Linie durch **bewährte Praktiken für die Lagerung oder die Ausbringung auf Böden** reduziert werden. Außerdem kann **verändertes Futter** die Stickstoffverwertung durch die Tiere verbessern und die Stickstoffausscheidungsraten aus dem Dung verringern (Samer 2015; Sajeev et al. 2018). Eine **verkürzte Lagerungszeit, das Abdecken des Dungs und die Vermeidung von Stroh-/Heueinstreu** können die Emissionen aus gelagertem Dung erheblich reduzieren (Climate Focus; CEA 2014). Fermenter können Gülle in Methan für die energetische Nutzung umwandeln. **Gülle kann auch recycelt und als Kompost** verwendet werden oder synthetische Düngemittel teilweise ersetzen, sofern sie mit guten Praktiken für ihre Ausbringung kombiniert wird. **Integrierte Ackerbau- und Viehzuchtsysteme** sind ein Beispiel dafür, wie die Ausbringung von Dung die landwirtschaftliche Produktivität steigern und den Einsatz von Mineraldüngern verringern kann (Reddy 2016).

- **Reduzierte Emissionen aus der Viehhaltung**: Der Tierhaltungssektor hat große Auswirkungen auf den Verbrauch natürlicher Ressourcen und die Lebensgrundlagen und ist für etwa 16,5 % der anthropogenen Treibhausgasemissionen verantwortlich (Twine 2021). **Verbessertes Weidemanagement, optimierte Zucht, Gesundheitsüberwachung und Krankheitsvorbeugung sowie höherwertiges Futter haben ein hohes Minderungspotenzial** (FAO 2013a). Die Verringerung der THG-Emissionsintensität pro Einheit Viehbestand durch diese Maßnahmen kann zu absoluten Emissionssenkungen beitragen, solange die gesamte Viehproduktion begrenzt ist (ebd.). Es ist zu beachten, dass Maßnahmen, die die Produktivität der Viehbestände verbessern, zwar die Emissionsintensität verringern, aber aufgrund der höheren Leistung der Tiere im Allgemeinen mit höheren absoluten Emissionswerten verbunden sind. Diese Maßnahmen würden nur dann zu einem Rückgang der absoluten Emissionen führen, wenn gleichzeitig die **Tierzahlen reduziert werden** (FAO 2017).

- **Kohlenstoffspeicherung in landwirtschaftlichen Böden**: Terrestrische Böden speichern schätzungsweise doppelt so viel Kohlenstoff wie derzeit in der Atmosphäre enthalten ist (Ciais et al. 2013). Um den Verlust von Kohlenstoff aus Böden zu verhindern, müssen gesunde Ökosysteme erhalten und ihre Zerstörung gestoppt werden. Auf landwirtschaftlich genutzten Böden kann der Bodenkohlenstoffgehalt erhöht werden, indem **mineralische und organische Düngemittel eingesetzt werden, Ernterückstände im Boden verbleiben, Agroforstwirtschaft betrieben wird, der Boden weniger stark bearbeitet wird und die Fruchtfolge verbessert wird. Der Anbau von mehrjährigen Kulturen oder Deckfrüchten** ist eine weitere Möglichkeit, den in den Böden gespeicherten Kohlenstoff zu erhöhen. Um die Fruchtfolgen zu verbessern, sollten Kulturen aus verschiedenen Kategorien angebaut werden (Primär- und Sekundärgetreide, Körnerleguminosen, Zwischenfutteranbau und in geringerem Maße Ölsaaten, Gemüse und Hackfrüchte). In Systemen mit Nährstoffmangel kann **zusätzlicher externer Dünger** eingesetzt werden, um den in den Böden gespeicherten Kohlenstoff zu erhöhen. Auf Grünland erhöht eine **optimale Beweidung** die Kohlenstoffspeicherung im Boden (Paustian et al. 2016). Außerdem wird diskutiert, exogenen Kohlenstoff wie Kompost oder Biokohle in den Boden einzubringen, um den Gehalt an Kohlenstoff zu erhöhen. Inwieweit solche exogenen Kohlenstoffeinträge dazu beitragen, die Emissionen insgesamt zu reduzieren, muss jedoch im Rahmen einer umfassenderen Lebenszyklusbewertung bewertet werden. Die Erhöhung des in den Böden gespeicherten Kohlenstoffs bringt zahlreiche andere ökologische und soziale Vorteile mit sich.

- **Reduzierte Treibhausgasemissionen aus dem Reisanbau**: Die globalen anthropogenen $CH_4$-Emissionen aus dem Reisanbau betrugen zwischen 2008 und 2017 25-37 Mt/Jahr (0,7 - 1,03 Gt $CO_2e$) (IPCC 2021), und Schätzungen für 2019 gehen von globalen $CH_4$-Emissionen aus Rohreis in Höhe von 24,08 Mt (0,67 Gt $CO_2e$) aus (FAO 2021a). **Änderungen der Bewirtschaftungsmethoden** können die $CH_4$-Emissionen aus dem Reisanbau verringern. Inwieweit dies insgesamt zum Klimaschutz beiträgt, hängt jedoch auch davon ab, wie sich die Änderungen in der Bewirtschaftung auf die $N_2O$-Emissionen auswirken, da verringerte $CH_4$ zu mehr $N_2O$-Emissionen führen können und umgekehrt (Yagi 2018; Kritee et al. 2018). **Die Bewässerungsmethoden von Reisfeldern** und insbesondere, welche Methoden zur Überflutung der Felder verwendet werden, beeinflussen die $CH_4$-Emissionen wesentlich (IPCC 2006), da kontinuierlich überflutete Reisfelder mehr Emissionen erzeugen als solche, die belüftet werden (IRRI 2007). Die **Belüftung** kann durch eine periodische Entwässerung des Reisfeldes erreicht werden, die in der Mitte der Vegetationsperiode (**Mid-Season Drainage**) oder mehrmals während der Vegetationsperiode (**Alternate Wetting and Drying - AWD**) durchgeführt werden kann. Eine weitere Alternative besteht darin, die Überflutung durch eine **kontrollierte oder periodische Bewässerung** zu ersetzen, die zwar zu erhöhten $N_2O$-Emissionen führen kann, aber dennoch einen positiven Gesamteffekt auf die THG-Emissionen hat (Hussain et al. 2014). Weitere Optionen zur Verringerung der $CH_4$-Emissionen aus dem Reisanbau sind **verbesserte Methoden zur Nutzung von Reisstroh, verbesserter Düngemitteleinsatz, veränderte Anbaumethoden sowie verbesserte Reissorten**.

- **Verbrennungspraktiken**: Beim Verbrennen von Ernterückständen werden Getreidestoppeln nach der Ernte verbrannt, um die Zeit zwischen Ernte und Aussaat zu verkürzen. Sie erhöht die Verschmutzung durch Ruß (mit negativen Auswirkungen auf die menschliche Gesundheit) und die Treibhausgasemissionen, beeinträchtigt die Bodenfruchtbarkeit und birgt das Risiko unkontrollierter Brände. In Teilen Indiens, Chinas und Südostasiens sind Verbrennungspraktiken nach wie vor üblich, da die rasche Intensivierung des Anbaus wirtschaftliche und praktische Grenzen für ein gutes Management von Ernterückständen gesetzt hat. Ernterückstände von Reis, der in den Tropen angebaut wird, können effektiv als Mulch, Kompost, Biokohle oder für die Erzeugung von Bioenergie genutzt werden (Bhuvaneshwari et al. 2019).

#### Maßnahmen auf der Nachfrageseite

Um die Emissionen aus der Landwirtschaft zu verringern, müssen neben einer Änderung der landwirtschaftlichen Praktiken auf der Angebotsseite auch auf der Nachfrageseite Maßnahmen zur Verringerung der Emissionen aus der Lebensmittelproduktion ergriffen werden. Maßnahmen auf der Nachfrageseite zur Änderung von Produktions- und Konsummustern können nicht nur die Emissionen reduzieren, sondern auch Druck auf die Landnutzung verringern und die Wiederherstellung natürlicher Ökosysteme und Wälder ermöglichen, da weniger Flächen für die landwirtschaftliche Nutzung benötigt werden (UBA 2020). Drei wichtige Ansätze zur Verringerung der Emissionen aus der Landwirtschaft auf der Nachfrageseite sind:

- **Reduzierte Lebensmittelverschwendung und -verluste**: Die FAO (2019a) definiert Lebensmittelverluste und -verschwendung als die Verringerung der Quantität oder Qualität von Lebensmitteln entlang der Lieferkette. Schätzungsweise gehen von den insgesamt produzierten Lebensmitteln zwischen 25 und 30 % verloren (IPCC 2019a). Der Verlust von genießbaren Lebensmitteln sowie die Verschwendung von Lebensmitteln durch Einzelhändler und Verbraucher führen zu höherer landwirtschaftlicher Produktion, was wiederum die Treibhausgasemissionen und den Gesamtdruck auf die natürlichen Ressourcen erhöht (Hiç et al. 2016). Die Gründe für Lebensmittelverluste und -verschwendung unterscheiden sich in Industrie- und Entwicklungsländern, in den verschiedenen Regionen und bei den verschiedenen Warengruppen erheblich. Sie betreffen alle Stufen der Lieferkette und umfassen Schädlinge, Naturkatastrophen, Wetterereignisse, schlechte landwirtschaftliche Praktiken, unzureichende Lagermöglichkeiten, schlechtes Handling bei der Verarbeitung und des Transports, Bedingungen des Markts, Verpackungsdesign von Unternehmen, Umgang mit Verfallsdaten, Präferenzen von Verbrauchern und individuelles Verhalten (IPCC 2019b; FAO 2019; HLPE 2014; Poore und Nemecek 2018; WWF 2021). Um die Lebensmittelverschwendung in verschiedenen Regionen der Welt zu bekämpfen, stehen **technische Optionen** zur Verfügung, darunter verbesserte Erntetechniken, eine verbesserte Lagerung in den landwirtschaftlichen Betrieben und ein verbesserter Transport und Vertrieb von Lebensmitteln, eine bessere Infrastruktur für die Lagerung von Lebensmitteln, die Verkürzung der Lieferketten (neue Verkaufsformen, z. B. Direktverkauf) oder die Stärkung der Position der Lebensmittelproduzenten in der Lieferkette sowie eine bessere Verpackung (IPCC 2019b, S. 58-60; HLPE 2014). Darüber hinaus sind **Verhaltensänderungen** erforderlich, um die Lebensmittelverschwendung zu reduzieren, z. B. die Akzeptanz von nicht ganz einwandfreiem Obst und Gemüse, eine höhere Sensibilität für die Auswirkungen der Lebensmittelverschwendung auf globaler Ebene und ein besseres Management beim Kauf und der Verwendung von Lebensmitteln zu Hause (Rosenzweig et al. 2020).

- **Änderung der Ernährungsgewohnheiten**: Durch veränderte Ernährungsgewohnheiten können die Ernährungssicherheit gestärkt und die Treibhausgasemissionen gesenkt werden. Es ist jedoch politisch heikel, auf Ernährungsgewohnheiten einzuwirken, weil dies als Eingriff in die Entscheidungsfreiheit der Menschen verstanden werden kann und etablierte Gewohnheiten tief in sozialen und kulturellen Traditionen verwurzelt sein können, die sich nur schwer durchbrechen lassen. Eine nachhaltige Änderung der Ernährungsgewohnheiten beinhaltet eine **Verringerung des Pro-Kopf-Kalorienverbrauchs (in Regionen mit Überkonsum) sowie die Umstellung auf eine pflanzenreiche Ernährung**. **Der Verzicht auf tierische Produkte** in der Ernährung verringert die Treibhausgasemissionen im Zusammenhang mit der Ernährung, wobei der Verzicht auf Rindfleisch eine besonders wichtige Rolle spielt (Clark et al. 2020; WRI 2016). Eine Umstellung auf alternative, gesündere Ernährungsweisen, die Nachhaltigkeitsaspekte berücksichtigen, d. h. weniger Fleisch und Milchprodukte (FAO 2020), könnte dazu beitragen, die Gesundheits- *und* Klimakosten bis 2030 zu senken. Darüber hinaus werden heute mehr als 40 % der weltweiten Erntekalorien als Viehfutter verwendet (Pradhan et al. 2013). Bei einer radikalen Änderung der aktuellen Ernährungsgewohnheiten würde die derzeitige Pflanzenproduktion ausreichen, um eine prognostizierte Weltbevölkerung von 9,7 Milliarden Menschen im Jahr 2050 zu ernähren (Berners-Lee et al. 2018). Die Umstellung der Ernährung hat daher großes Potenzial, die Ernährungssicherheit für die Weltbevölkerung zu stärken (UBA 2021).

- **Reduzierte Entwaldung zur Erschließung neuer Acker- und Grünlandflächen**: Die Nettoentwaldung im nächsten Jahrzehnt zu stoppen, ist eine Schlüsselkomponente der Emissionspfade, die mit dem 1,5°C-Limit vereinbar sind. Etwa 60 % der Entwaldung in den Tropen wird durch die Ausweitung der landwirtschaftlichen Nutzflächen für Ackerland, Weiden und Plantagen verursacht, wobei Rinder und Ölsaaten den größten Anteil haben

(Pendrill et al. 2019). Wenn die Nachfrage nach diesen Produkten sinkt, wird weniger Land für den Anbau von Futtermitteln und Energiepflanzen benötigt, was wiederum den Druck auf die Ökosysteme verringert. Die weitere Ausdehnung der Landwirtschaft sowie die damit verbundene Entwaldung zu verringern, hat weitere positive ökologische und soziale Nebeneffekte, da natürliche Lebensräume erhalten bleiben und der Verlust der biologischen Vielfalt reduziert wird. **Maßnahmen zur Verringerung der Entwaldungsemissionen zielen (1) direkt darauf ab, bewaldete Gebiete zu erhalten**, und umfassen (2) **Maßnahmen, die die Nachfrage nach neuen landwirtschaftlichen Flächen und deren Ausweitung in die Wälder verringern**.

#### Hemmnisse für ehrgeizige Klimaschutzmaßnahmen im Agrarsektor

Der IPCC-Sonderbericht über Klimawandel und Land (IPCC 2019b) unterscheidet sechs Typen von Hemmnissen für Klimaschutz im Agrarsektor: **Ökonomische Barrieren** bedeuten, dass Marktstrukturen und Marktakteure einem ambitionierteren Klimaschutz in der Landwirtschaft entgegenwirken, z. B. durch niedrige Weltmarktpreise, etablierte Infrastruktur, fehlende Absatzmärkte für klimafreundliche Lebensmittel etc. **Politische/rechtliche Barrieren** umfassen bestehende Gesetze und Verordnungen, finanzielle Anreize oder Ressourcen und die Ausgestaltung von Förderinstrumenten auf nationaler, regionaler und internationaler Ebene, die teilweise kontraproduktiv für ambitionierte Klimaschutzmaßnahmen in der Landwirtschaft sind. **Technische Barrieren** beziehen sich auf mangelndes Wissen oder die Verfügbarkeit geeigneter Technologien. **Soziokulturelle Barrieren** ergeben sich aus Verhaltens- und Lebensstilmustern oder Werten, die unserer Ernährung und Einstellung zu Lebensmitteln zugrunde liegen. Auch **institutionelle Hindernisse** aufgrund unterschiedlicher Zuständigkeiten und Kompetenzaufteilungen können Reformprozesse erschweren. Zu den **biophysikalischen oder umweltbedingten Hindernissen** gehören Faktoren, die die fruchtbaren Landflächen oder die Nahrungsmittelproduktion einschränken, wie Versalzung, Temperaturanstieg oder extreme Wetterereignisse wie Überschwemmungen oder Dürre.

Die Hindernisse, die für die verschiedenen Optionen für mehr Klimaschutz in der Landwirtschaft ermittelt wurden, können nach verschiedenen Ebenen kategorisiert werden, auf denen sie wirken. Es ist zu beachten, dass die Relevanz spezifischer Hindernisse stark von den lokalen Gegebenheiten abhängt. So bestimmen z. B. die biophysikalischen Bedingungen den Rahmen für geeignete Minderungsoptionen. Dazu gehören die klimatischen Bedingungen und die Bodenstruktur, aber auch die Größe der landwirtschaftlichen Betriebe und die Art der vorherrschenden landwirtschaftlichen Tätigkeiten. Die Bewertung, Planung und Umsetzung nationaler Klimapolitiken im Agrarsektor sowie Ansätze zur Überwindung bestehender Barrieren müssen daher kontextspezifisch sein (OECD 2017; IPCC 2019a).

Für die **Ebene der landwirtschaftlichen Betriebe** wurden die folgenden Hemmnisse identifiziert:

- Ökonomische Hindernisse
  - Wenn Minderungsmaßnahmen nicht mit **wirtschaftlichen Vorteilen** für die Landwirt*innen einhergehen, hemmt dies deren Umsetzung. Wenn eine Änderung in der Bewirtschaftungspraxis **hohe Kosten für die Einführung/Transaktion auf Betriebsebene** mit sich bringt, insbesondere im Hinblick auf die Kapitalkosten, wird dies die Landwirte ebenfalls davon abhalten, ihre Praktiken zu ändern (OECD 2017; Smith et al. 2007a; Mills et al. 2020). Der **fehlende Zugang zu Krediten** für Investitionen in Infrastruktur, Maschinen und Geräte verstärkt diese Barriere (OECD 2017; Wageningen University 2014). Fehlende finanzielle Mittel für Investitionen in bessere Ernte- und Lagertechnologien wurden ebenfalls als Hindernis für die

Verringerung von Lebensmittelverlusten und -verschwendung auf betrieblicher Ebene identifiziert (FAO 2019a). Überdies steht die **Ungewissheit über die Auswirkungen veränderter landwirtschaftlicher Praktiken** im Wege (Kragt et al. 2017).

- Solche Hindernisse werden durch **strukturelle Faktoren wie das Alter der Landwirte oder die Betriebsgröße** verstärkt, die beeinflussen, inwieweit Innovationen umgesetzt werden (OECD 2017; Mills et al. 2020; Knowler und Bradshaw 2007).

► Politische/rechtliche Barrieren:

- Die Entscheidung einer*eines Landwirtin*Landwirts, klimafreundliche Maßnahmen zu ergreifen, hängt davon ab, **wie Besitz und Nutzung von Land geregelt sind**. Dabei wirken sich Pachtverträge positiv auf die Bereitschaft aus, klimafreundliche Maßnahmen wie eine nachhaltige Bodenbewirtschaftung umzusetzen (OECD 2017; Aryal et al. 2020; Congressional Research Service 2020).
- **Fehlende institutionelle Unterstützung, Beratung oder Informationen** für die Landwirt*innen wurden ebenfalls als Hindernis für die Einführung nachhaltigerer landwirtschaftlicher Bewirtschaftungsmethoden festgestellt (Mills et al. 2020).

► Technische Barrieren

- **Fehlende Technologien oder Kapazitäten** von Kleinbauern können ebenfalls ein Hindernis für die Änderung landwirtschaftlicher Praktiken sein, z. B. die Beibehaltung von Verbrennungspraktiken von landwirtschaftlichen Abfällen in Indien, China und Südostasien (Bhuvaneshwari et al. 2019), oder die Umstellung auf Agroforstwirtschaft.

► Soziokulturelle Barrieren

- Weitere Faktoren auf Betriebsebene betreffen **persönliche Einstellungen, Traditionen und Praktiken**, die beeinflussen, inwieweit Minderungsmaßnahmen akzeptiert werden (OECD 2017; Mills et al. 2020). Auch eine Aversion gegenüber Risiken steht z. B. dem verringerten Einsatz von Düngemitteln entgegen (Robertson und Vitousek 2009). Darüber hinaus können Geschlechterrollen als soziales Hindernis für den Zugang zu Informationen wirken (Aryal et al. 2020). Insbesondere im Kontext der kleinbäuerlichen Landwirtschaft sind die soziale und kulturelle Rolle der Viehhaltung sowie die wirtschaftliche Abhängigkeit von der Viehhaltung starke Argumente gegen eine Verringerung der Anzahl der Tiere (Herrero et al. 2016; Thornton 2010).
- Darüber hinaus hat sich gezeigt, dass **mangelndes Bewusstsein** für den Klimawandel und seine Folgen sowie **fehlendes Wissen** über Minderungsmaßnahmen und deren Vorteile und deren Umsetzung Landwirt*innen in Südostasien davon abhalten, in Klimaschutzmaßnahmen zu investieren (Aryal et al. 2020). Studien aus Indien und den USA haben gezeigt, dass den Landwirten beispielsweise das Bewusstsein für den Zusammenhang zwischen Düngereinsatz und Klimawandel fehlt und sie von Wirtschaftsakteuren mit Eigeninteressen Ratschläge für den Düngereinsatz erhalten (Stuart et al. 2013; Pandey und Diwan 2018).

► Biophysikalische/umweltbezogene Barrieren

- Die **Reversibilität von Emissionsminderungen** oder der Kohlenstoffbindung in der Landwirtschaft kann der Umsetzung von Minderungsmaßnahmen entgegenwirken, z.B.

indem Landwirte keine klimafreundlichen Anbaupraktiken umsetzen, weil die Ergebnisse möglicherweise nicht dauerhaft sind (Aryal et al. 2020).

Auf **nationaler Ebene** behindern weitere Barrieren die Verbesserung der Emissionsminderung im Agrarsektor:

- Ökonomische Hindernisse
  - Erstens rührt der Widerstand gegen Minderungsoptionen von den **wahrgenommenen potenziellen negativen Auswirkungen auf die Produktion** her, insbesondere in Ländern, in denen die Landwirtschaft ein wichtiger Wirtschaftszweig ist (OECD 2017). Wenn die Entwaldung wirtschaftliche Vorteile bringt, kann der politische Wille zur Umsetzung strengerer Vorschriften schwach sein (Kalaba 2016). **Wirtschaftliche Ziele zur Steigerung der landwirtschaftlichen Erträge** können auch als Hindernis für nachhaltigere Formen der landwirtschaftlichen Produktion wirken.
  - In Regionen, in denen die **Ernährungssicherheit** das vorrangige politische Ziel ist, kann die Absicht, das Produktionsniveau zu erhöhen, sogar den Schutz kohlenstoffreicher Böden verhindern, die noch nicht für landwirtschaftliche Zwecke genutzt werden (Minasny et al. 2017).
  - Zweitens kann die **Zusammenarbeit mit der Industrie** Veränderungen im Pflanzenbau behindern, z. B. wenn Verträge abgeschlossen wurden, die sich auf die Erträge konzentrieren, oder wenn die Beziehungen zu den Verarbeitungsbetrieben schon lange bestehen (OECD 2017).
- Politische/gesetzliche Hindernisse
  - **Politische Maßnahmen zur Unterstützung der Produktion, wie z. B. Betriebsmittelsubventionen oder Steuerbefreiungen**, können Hindernisse für klimafreundliche landwirtschaftliche Praktiken darstellen (OECD 2017), da sie implizieren, dass mit konventionellen, intensiven, monokulturellen Anbausystemen mehr Einnahmen erzielt werden können (Oberč und Arroyo Schnell 2020). So fördern beispielsweise Subventionszahlungen, die sich nach dem Umfang der Produktion richten, einen übermäßigen Einsatz von Düngemitteln (Robertson und Vitousek 2009). Ebenso zielen die bestehenden finanziellen Anreize häufig auf den Bau von anaeroben Fermentern und nicht auf den Wert des Outputs ab, was die Landwirte nicht dazu anregt, ihr Düngermanagement zu verbessern. Bestehende Düngemittelsubventionen verhindern, dass synthetischer Dünger durch Gülle ersetzt wird (Tan et al. 2021). Der größte Teil der direkten Produktionssubventionen für Landwirt*innen auf globaler Ebene geht an die größten Betriebe, die besser in der Lage sind, Preis- und Einkommensschwankungen selbst zu bewältigen als Kleinbauern (Searchinger 2020). Nur ein kleiner Teil dieser Unterstützung wird für den Klimaschutz verwendet, obwohl die Umweltauflagen für die Zahlungen an den Agrarsektor in den letzten Jahren strenger geworden sind (Weltbank 2020).
  - Auch **Eigentumsrechte** können Klimaschutzmaßnahmen im Agrarsektor entgegenwirken. Sind die Eigentumsverhältnisse nicht eindeutig geklärt, wirkt dies Änderungen der Bewirtschaftung entgegen (Smith et al. 2007a).
- Technische Hindernisse

- **MRV-Systeme**, die festlegen, wie Emissionen berichtet und angerechnet werden, können auch auf nationaler Ebene Hindernisse darstellen. Viele Minderungsmaßnahmen werden in der Berichterstattung in Treibhausgasinventaren nicht erfasst, wenn die Länder nicht die komplexen Methoden (Tier 3) der IPCC-Inventarrichtlinien anwenden. Dies schmälert die Anerkennung für die Umsetzung von Klimaschutzmaßnahmen für Regierungen (OECD 2019b). Andere positive Effekte auf die Umwelt werden in dieser Bilanzierung überhaupt nicht berücksichtigt. Außerdem fehlen Daten zu Emissionen durch veränderte Bodenkohlenstoffvorräte infolge von Versiegelung, Landnutzungsänderungen oder Bodennutzung in Produktionsprozessen (OECD 2017; Bispo et al. 2017).
- In Bezug auf Lebensmittelverschwendung und -verluste stellt der Mangel an verlässlichen Daten ein großes Hindernis für wirksame Maßnahmen dar (FAO 2019a).

► Soziokulturelle Barrieren

- Darüber hinaus kann ein **Mangel an Bildung und Bewusstsein** für die negativen Auswirkungen der Landwirtschaft auf den Klimawandel ein Hindernis für klimafreundlichere Politiken auf der Ebene der politischen Entscheidungsträger darstellen (OECD 2017).

► Institutionelle Barrieren

- Das Fehlen einer gut konzipierten Klimapolitik, die den Landwirtschaftssektor einbezieht, kann als Hindernis für Klimaschutzmaßnahmen wirken, da es keine Anreize für diese Maßnahmen gibt (OECD 2017). Dies kann aus einem fehlenden Ziel oder einer Vision für eine nachhaltige Landwirtschaft resultieren, sodass kohärente politische Anreize für nachhaltige Praktiken verhindert werden (Oberč und Arroyo Schnell 2020). Darüber hinaus behindert fehlende Koordinierung zwischen verschiedenen Regierungsebenen oder Ministerien die Umsetzung ehrgeiziger Klimaschutzmaßnahmen (Aryal et al. 2020). Für die Regierungen im globalen Süden stellen schwache Durchsetzungskapazitäten sowie unterbesetzte und unterfinanzierte Umweltbehörden Hindernisse für eine wirksame Regulierung der Entwaldung für landwirtschaftliche Zwecke dar (Furumo und Lambin 2020).

Hemmnisse auf **internationaler Ebene** ergeben sich aus den folgenden Aspekten:

► Ökonomische Hindernisse

- Wirtschaftlicher Wettbewerb zwischen Ländern, der die Umsetzung von Minderungsmaßnahmen behindert: strengere Minderungsmaßnahmen in einem Land benachteiligt dieses Land im Wettbewerb mit anderen Ländern und kann zur **Verlagerung von $CO_2$-Emissionen** in andere Länder führen (OECD 2017). Insbesondere Maßnahmen zur Reduzierung der Emissionen aus der Viehzucht im globalen Norden würden dazu führen, dass zwei Drittel der eingesparten Emissionen durch erhöhte Methanemissionen im globalen Süden aufgrund der Verlagerung von der heimischen Produktion auf importierte Viehzuchtprodukte ausgeglichen würden (Key und Tallard 2012).
- Die Globalisierung der Lebensmittelindustrie hat große Akteure mit globalem Einfluss auf die Ernährungsgewohnheiten hervorgebracht. Infolgedessen wird die Lebensmittelindustrie von **wirtschaftlichen Eigeninteressen** angetrieben, die politisch nur schwer zu bekämpfen sind (GRAIN; IATP 2018).

- Da der Agrarhandel globalisiert ist, gibt es **lange Lieferketten** für landwirtschaftliche Erzeugnisse, die indirekt zur Entwaldung beitragen (z. B. die Nachfrage nach Palmölprodukten). Da viele Akteure beteiligt sind, sind die Regulierung und die Überwachung der Entwaldung auf globaler Ebene eine Herausforderung.

► Politische/rechtliche Hindernisse

- Unzureichende finanzielle Unterstützung kann ebenfalls ein Hindernis für Klimaschutz in der Landwirtschaft darstellen (Aryal et al. 2020).

- Niedrige Weltmarktpreise und die Abhängigkeit der Kleinbauern von **asymmetrischen Handelsstrukturen** stehen der Bekämpfung von Nahrungsmittelverlusten und -verschwendung im Wege, da sie dazu führen können, dass Landwirt*innen aufgrund von Stornierungen in letzter Minute nicht in der Lage sind, überschüssige Nahrungsmittel zu ernten (WWF 2021). Machtungleichgewichte zwischen Landwirten und Einzelhändlern sind strukturelle Faktoren, die das Einkommen der Landwirte niedrig halten und den Status quo aufrechterhalten (WWF 2021).

- Klimaschutzmaßnahmen im Agrarsektor können mit **internationalem Handelsrecht** kollidieren, z. B. wenn die Unterstützung nationaler Erzeuger, die die THG-Emissionen in ihrer Produktion reduzieren, gleichzeitig dazu beiträgt, die Exporte zu steigern oder Importe zu ersetzen; wenn "klimaunfreundliche" Produkte und Produktionsmethoden an der Grenze besteuert werden oder wenn die Kennzeichnung zur Information der Verbraucher nicht auf international vereinbarten Standards beruht (Häberli 2018).

- **Freihandelsabkommen** können Regierungen dazu veranlassen, Subventionen so zu verlagern, dass sie weniger marktverzerrend sind, dies hat aber keine signifikanten Auswirkungen auf die globalen Emissionen (Searchinger 2020).

► Technische Barrieren

- **Fehlende Messgrößen und Indikatoren** stellen ein weiteres Hindernis für die Umsetzung von Klimaschutzmaßnahmen im Agrarsektor dar. Wenn es keine quantitativen Belege für den Nutzen einer Maßnahme gibt, wird es schwierig sein, Landwirt*innen, Verbraucher*innen oder politische Entscheidungsträger*innen davon zu überzeugen, Veränderungen zu unterstützen (IUCN 2020).

- Auch fehlen **klare wissenschaftliche Zielvorgaben** für eine gesunde Ernährung, was den Übergang zu einem nachhaltigen globalen Ernährungssystem behindert (Willett et al. 2019).

- Aufgrund **fehlender Standards für die Datenerhebung**, keiner gemeinsam vereinbarten Bewertungsmethode und unterschiedlicher Definitionen gibt es ein großes Hindernis bei der Ermittlung der Ursachen und des Ausmaßes von Lebensmittelverlusten und -verschwendung (HLPE 2014).

- Im Hinblick auf die Eindämmung der Entwaldung stellen die **Schwierigkeiten bei der Überwachung und Kontrolle, d. h. die mangelnde Transparenz**, ein Hindernis für wirksame internationale Maßnahmen dar. Dies gilt sowohl für die tatsächliche Abholzung von Bäumen vor Ort als auch für Lieferketten, an denen mehrere Akteure beteiligt sind, die möglicherweise international verteilt sind, was die Herausforderung, jemanden zur Rechenschaft zu ziehen, noch erhöht (NewClimate Institute 2021).

Die **Hemmnisse auf der Verbraucherebene** betreffen hauptsächlich soziokulturelle Aspekte wie Ernährungskultur und -tradition. Die Umstellung der Ernährung hat Auswirkungen auf die subjektive Entscheidungsfreiheit der Menschen sowie auf soziale und kulturelle Gewohnheiten und ist daher politisch heikel. Hinzu kommt, dass die Vorteile einer nachhaltigen Ernährung bisher nicht richtig kommuniziert wurden und die Umstellung auf eine solche Ernährung von den Verbrauchern als störend empfunden wurde (WRI 2016). Ein Hindernis für die Verwendung von Insektenproteinen in der Ernährung ist die geringe Akzeptanz von Lebensmitteln auf Insektenbasis in westlichen Gesellschaften (Wendin und Nyberg 2021). Darüber hinaus fehlen Regelungen, um Insekten in die Lebensmittelversorgungssysteme westlicher Länder zu bringen (Dobermann et al. 2017). **Essgewohnheiten und hohe Ansprüche** an die Form, das Aussehen und die ganzjährige Verfügbarkeit sind außerdem ein treibender Faktor für Lebensmittelverluste und -verschwendung auf internationaler Ebene.

### Empfehlungen für Maßnahmen

Der Wandel, der für die Veränderung des globalen Lebensmittelsystems erforderlich ist, erfordert Maßnahmen auf allen Ebenen.

Landwirt*innen, Betriebsleiter*innen und lokale Gemeinschaften sind letztlich die Akteure, die Veränderungen der landwirtschaftlichen Bewirtschaftungspraxis umsetzen. **Auf der Ebene der (kleinen) landwirtschaftlichen Betriebe ist der Aufbau von Kapazitäten erforderlich, um Informationen an die lokalen Akteure weiterzugeben und das Wissen über die Vorteile nachhaltiger landwirtschaftlicher Praktiken zu verbessern.** Um beispielsweise gegen Lebensmittelverluste und -verschwendung vorzugehen, sind Schulungen und Weiterbildungen für Landwirt*innen (sowie für andere Akteure entlang der Lieferkette) notwendig, um Praktiken zu ändern (HLPE 2014).

Bei der Bereitstellung von Schulungen und finanzieller Unterstützung, kann es von Vorteil sein, **lokale Akteure und lokales Wissen einzubeziehen**. In diesem Zusammenhang spielen Wissensnetzwerke eine entscheidende Rolle. Wissenstransfer von Landwirten zu Landwirten kann helfen, die langfristigen Vorteile nachhaltiger Landwirtschaft zu verstehen (Aryal et al. 2020).

Darüber hinaus brauchen Landwirt*innen **finanzielle Unterstützung und die richtigen wirtschaftlichen Anreize**, um ihre landwirtschaftlichen Praktiken zu ändern. Zahlungen zum Ausgleich wahrgenommener finanzieller Risiken können solche Veränderungen unterstützen. Mikrofinanzinitiativen, die finanzielle und technologische Unterstützung bieten, können ebenfalls dazu beitragen, Nahrungsmittelverluste und -verschwendung zu bekämpfen,

Auf **nationaler und subnationaler Ebene** müssen Gesetze und Vorschriften so gestaltet werden, dass sie Anreize zur Umstellung der Produktion auf nachhaltigere Alternativen bieten. Insbesondere auf staatlicher Ebene muss die **öffentliche Unterstützung auf nachhaltige Praktiken umgelenkt werden** (Weltbank 2020; Climate Focus; CEA 2014; FAO und UNDP 2021). Finanzielle Anreize sollten auf Ökosystemleistungen basieren und nicht nur an die Größe der Betriebe oder den Ertrag gebunden sein (Robertson und Vitousek 2009). Direktzahlungen sollten auch an die Bedingung geknüpft werden, dass kein neues Land gerodet wird, es sei denn, dies ist zur Gewährleistung der Ernährungssicherheit unvermeidlich (Weltbank 2020).

Die **Agrarsubventionen müssen reformiert werden**. In Ländern mit hohem Einkommen müssen schädliche Subventionen abgeschafft werden. Die Unterstützung sollte nicht an die Höhe der Produktion gekoppelt sein, und es sollten insbesondere Anreize für die Produktion von nahrhaften Lebensmitteln für eine gesunde Ernährung geschaffen werden. In Ländern mit mittlerem Einkommen sollten die Subventionen auch von der Produktion oder den Produktionsmitteln entkoppelt werden. Negative Auswirkungen für einkommensschwache

Gruppen sollten durch geeignete Ausgleichsmaßnahmen abgeschwächt werden. In Ländern mit niedrigem Einkommen trägt außerdem ein freierer Markt zu höheren Einkommen für Landwirt*innen und nachhaltigere Produktionsweisen bei. Subventionen des Konsums in Verbindung mit Maßnahmen zur sozialen Abfederung könnten die gesunde Ernährung in ärmeren Ländern unterstützen. Durch die Entkopplung der Zahlungen von der Produktion, bestimmten Rohstoffen oder Erträgen können auch Kleinbauern gezielter gefördert werden. Bei der Umwidmung der Agrarförderung muss deutlich gemacht werden, dass es nicht darum geht, die Unterstützung für die Landwirte zu kürzen, sondern sie so umzuverteilen, dass sie für die Gesellschaft als Ganzes von größerem Nutzen ist (FAO und UNDP 2021).

**Gezielte Unterstützung und die Verknüpfung von inländischer Kreditvergabe mit politischen Maßnahmen und bewährten Praktiken** können Erzeuger bei der Umstellung auf eine nachhaltigere landwirtschaftliche Produktion und Waldnutzung (Global Canopy Programme 2015) sowie bei der Verringerung der Lebensmittelverschwendung unterstützen. Um (wahrgenommenen) wirtschaftlichen Risiken entgegenzuwirken, sollte öffentliche und/oder private Unterstützung für die Übergangszeit bereitgestellt werden, in der nachhaltigere Praktiken eingeführt werden (z. B. Anbau von Bäumen in Agroforstsystemen) (IUCN 2020). Wo möglich, sollte auch für die Stilllegung und Wiederherstellung von Flächen, die nicht dringend für landwirtschaftliche Zwecke benötigt werden, Förderung bereitgestellt werden. Es hat sich gezeigt, dass Systeme mit gestuften Zahlungen, mit denen Landwirt*innen für immer bessere Leistungen belohnt werden, den Klimaschutz eher fördern als die Festlegung von Mindestumweltstandards. Außerdem sollten Innovationen unterstützt werden, z. B. durch die Förderung neuer Technologien, die in größerem Umfang wirtschaftlich werden (Weltbank 2020). Finanzielle Anreize sollten an **hohe Umweltauflagen** geknüpft werden. Marktbasierte Instrumente werden in der Literatur häufig als Anreiz für weitere Minderungsmaßnahmen im Agrarsektor genannt (z. B. Smith et al. 2007b; Minasny et al. 2017). Projekte, die Maßnahmen zur Kohlenstoffspeicherung umsetzen, können jedoch in der Regel keine dauerhafte Speicherung von Kohlenstoff (über einen Zeitraum von Hunderten von Jahren bis Jahrtausenden) garantieren. Neben anderen Risiken für ihre ökologische Integrität (UBA 2022) untergräbt dies ihre Eignung als echte Option für den Ausgleich von Emissionen, die anderswo entstehen.

Finanzielle Unterstützung für die Umstellung auf nachhaltigere Praktiken sollte im Einklang mit **strengerer Regulierung** sein, z. B. in Bezug auf das Güllemanagement oder Kohlenstoffsteuern zur Verringerung der Treibhausgasemissionen aus der Tierhaltung oder dem Düngemitteleinsatz (Paustian et al. 2016; Minasny et al. 2017).[2] Bei der Ausgestaltung solcher Anreize muss sichergestellt werden, dass sie nicht zu höherer Produktion führen (wo dies zur Gewährleistung der Ernährungssicherheit nicht erforderlich ist) oder Emissionen in andere Länder verlagern (Thornton et al. 2007). Steuern sollten den Verbrauchern geeignete Signale über den ökologischen Fußabdruck von Produkten senden, um die Nachfrage nach landintensiven Produkten, insbesondere Fleisch, zu verringern (Boerema et al. 2016; Sisnowski et al. 2017). Die Beschaffungspolitik ist ein zusätzlicher Hebel zur Förderung einer gesunden Ernährung, die nachhaltigere landwirtschaftliche Praktiken voraussetzt, an Arbeitsplätzen, Schulen und anderen Orten, an denen Mahlzeiten öffentlich angeboten werden (Willett et al. 2019). Reformen zur Verbesserung der Besitz- bzw. Nutzungsverhältnisse können die Abholzung von Wäldern und nicht nachhaltige landwirtschaftliche Praktiken verringern, auch wenn dies ein heikles Thema ist (Angelsen 2010; UBA 2021).

[2] In den Programmen des US-Landwirtschaftsministeriums ist beispielsweise Minderung als Beitrag zum Naturschutz enthalten; Bestimmungen in der Gemeinsamen Agrarpolitik der EU verknüpfen Subventionszahlungen mit "Cross-Compliance"-Maßnahmen, zu denen die Erhaltung des organischen Kohlenstoffgehalts im Boden gehört (Louwagie et al. 2011).

Darüber hinaus ist es entscheidend, **kohärente politische Signale an den Agrarsektor** zu senden (OECD 2019a). Klima- und Umwelteinflüsse sollten bei allen politischen Entscheidungen, die sich auf landwirtschaftliche Systeme auswirken, berücksichtigt werden. Die Einbeziehung von subnationalen Akteuren des Lebensmittelsystems wie Landwirt*innen, Lebensmittelherstellern und Einzelhändlern kann dazu beitragen, starke nationale Rahmenbedingungen für die Umsetzung von Maßnahmen zur Minderung von Emissionen aus dem breiteren Lebensmittelsystem zu schaffen (Global Alliance for the Future of Food 2022). Es sind politische Maßnahmen erforderlich, die die sektoralen Emissionen für den gesamten Landnutzungssektor regeln, um eine Ausweitung der Produktion aufgrund von Effizienzsteigerungen oder höheren Gewinnen zu verhindern, insbesondere bei der Viehzucht (FAO 2013a). Eine bessere Koordinierung zwischen Gesundheits-, Landwirtschafts-, Wasser- und Umweltbehörden ist ebenfalls erforderlich, um die Kohärenz der politischen Maßnahmen für eine nachhaltige Ernährung sicherzustellen (WRI 2016; FAO und UNDP 2021).

Die Überwachung und Evaluierung von Maßnahmen ist notwendig, um ökologische Fortschritte und Verbesserungen der Politik im Laufe der Zeit voranzutreiben (Weltbank 2020). Dies gilt insbesondere für Maßnahmen gegen Lebensmittelverluste und -verschwendung sowie gegen die Entwaldung (Global Canopy Programme 2015).

**Um Hemmnisse auf internationaler Ebene zu beseitigen, müssen multilaterale Initiativen und Gipfeltreffen auf globaler Ebene einen angemessenen globalen Rahmen** für die Verwirklichung eines nachhaltigeren Lebensmittelsystems schaffen, indem sie Ziele und Standards festlegen und ein Forum für den kontinuierlichen Austausch bieten. Die UN-Gipfel für Ernährungssysteme, die Konferenzen der Vertragsparteien (COPs) im Rahmen des Übereinkommens über die biologische Vielfalt (CBD) sowie die UNFCCC bringen die globale Gemeinschaft zu diesem Zweck zusammen (FAO und UNDP 2021).

Darüber hinaus müssen **auf internationaler Ebene politische Regelungen und Handelsstrukturen geändert werden**, um die richtigen Anreize für eine nachhaltigere landwirtschaftliche Produktion zu setzen. Anpassungen der WTO-Regeln könnten notwendig sein, um Konflikte zwischen Klimaschutzmaßnahmen und Handelsrecht zu vermeiden (Häberli 2018). Es hat sich gezeigt, dass sich Steuern stärker auf den Verbrauch auswirken, wenn sie in größeren Regionen statt in einzelnen Ländern erhoben werden, wenn die Substitute ebenfalls besteuert werden und wenn die Steuern ausreichend hoch sind (WRI 2016). Die WTO kann eine zentrale Rolle bei der Koordinierung der Mitglieder spielen, damit diese konzertierte Anstrengungen unternehmen, um wettbewerbsverzerrende Maßnahmen abzubauen und gleichzeitig den Übergang zu nachhaltigerer Produktion zu unterstützen.

Den Landwirt*innen müssen **gerechtere Preise** gezahlt werden, damit sie ihre Ernte- und Feldbewirtschaftungstechniken verbessern können. Hohe Subventionen in einigen Ländern können die Weltmarktpreise drücken und damit die Einkommen anderer Agrarexporteure und lokaler Erzeuger schmälern. Kartelle im Zusammenhang mit der Nahrungsmittelproduktion und dem Handel sowie Finanzspekulationen mit Nahrungsmitteln haben starke negative Auswirkungen auf die Bevölkerung in Ländern mit niedrigem Einkommen, die von den globalen Märkten abhängig sind (IPCC 2019c). Marktregulierungen und Gesetze zum fairen Handel, die vertragliche Vereinbarungen zur gerechteren Aufteilung der Risiken zwischen Erzeugern und Einzelhändlern fördern, sind daher notwendig, z. B. um Landwirt*innen in die Lage zu versetzen, die Lebensmittelverschwendung auf betrieblicher Ebene anzugehen (WWF 2021).

Um insbesondere die Expansion der Landwirtschaft und die daraus resultierende Entwaldung zu bekämpfen, ist eine kontextspezifische Systemperspektive erforderlich, die sich mit den Faktoren in allen Elementen der Lieferkette befasst. Um alle Akteure entlang der Lieferkette in die Verantwortung zu nehmen, bedarf es **internationaler Regulierungen** (Europäisches Parlament 2020; Hughes und Terazono 2020). Die Entwicklung multilateraler öffentlich-privater Partnerschaften zur Vermeidung von Entwaldung und in der Lieferkette wäre ein Ansatz zur Bekämpfung der Entwaldung (Furumo und Lambin 2020).

Darüber hinaus **muss die Forschungsgemeinschaft mehr tun, um eine nachhaltige Umgestaltung der Landwirtschaft zu unterstützen**. Erstens wird die Festlegung gemeinsamer Definitionen, Messgrößen und Indikatoren dazu beitragen, den Nutzen der Ansätze für eine nachhaltige Landwirtschaft zu messen (Oberč und Arroyo Schnell 2020; Frison 2020). Auch müssen die Auswirkungen der landwirtschaftlichen Förderung (FAO und UNDP 2021) sowie politischer Maßnahmen auf die Bodengesundheit besser erforscht werden (Bispo et al. 2017). Auf internationaler Ebene ist mehr Zusammenarbeit erforderlich, um Standards und Leitlinien für ein besseres MRV von bodenbezogenen Emissionen zu entwickeln. Die Erfahrungen mit bewährten Praktiken zur Verringerung von Lebensmittelabfällen und -verlusten sollten regelmäßig auf internationaler Ebene zwischen Wissenschaft und Politik ausgetauscht werden, um eine globale Verbesserung zu erreichen und das öffentliche Interesse und die Debatte zu diesem Thema zu fördern.

Auf der **Ebene der Verbraucher*innen** spielen vor allem soziokulturelle und wirtschaftliche Barrieren eine Rolle. **Bildung und Wissensvermittlung sowie gesellschaftliche Dialogprozesse und Leitbilder** sind wichtige Treiber für die Überwindung solcher Barrieren. Fleischalternativen wie Fleischimitate (aus pflanzlichen Produkten), kultiviertes Fleisch und Insekten können die Umstellung auf eine nachhaltigere Ernährung unterstützen. Überzeugungsarbeit und Aufklärung sind ebenfalls notwendig, um das Wissen über Lebensmittelverluste und -verschwendung zu fördern und so einen Anreiz für Verhaltensänderungen zu schaffen. Dies muss durch eine Ausweitung der Produktstandards unterstützt werden, um die Standards für Form und Aussehen von Lebensmitteln, insbesondere von Obst und Gemüse, zu senken (WWF 2021). Darüber hinaus müssen Regelungen zur Haltbarkeitsetikettierung den Verbraucherinnen*Verbrauchern klare Signale geben (HLPE 2014). Darüber hinaus könnten **technische Optionen Verhaltensänderungen der Verbraucher** unterstützen, wie bessere Verpackungen oder die Möglichkeit, in Restaurants Essensreste mit nach Hause zu nehmen (HLPE 2014). Food-Banking durch NGOs, die überschüssige Lebensmittel verteilen, kann ebenfalls dazu beitragen, Lebensmittelverluste und -verschwendung zu reduzieren. Politische Regelungen sollten Spenden durch steuerliche Anreize begünstigen (HLPE 2014).

Generell sind die Hemmnisse auf Verbraucherebene, die einer nachhaltigeren und gesünderen Ernährung im Wege stehen, eng mit allgemeineren Fragen der Ungleichheit verbunden. Daher müssen nachhaltige Lebensmittel für alle Verbraucher*innen erschwinglicher gemacht werden, und es müssen "Nudging"-Ansätze (d.h. Anstoß-Impulse) angewandt werden, die die Verbraucher dazu bringen, "bessere Entscheidungen" zu treffen (z. B. indem nachhaltige Optionen standardmäßig angeboten oder gesündere Optionen attraktiver präsentiert werden) (Reisch et al. 2013). Die Verbesserung des sozialen Wohlergehens im Allgemeinen kann die Umstellung auf gesündere Ernährung unterstützen.

Um die beschriebenen Hindernisse zu beseitigen, müssen Akteure auf allen Verwaltungsebenen und entlang der gesamten Lieferkette einbezogen werden. Vorrangig sollten diejenigen Hindernisse in Betracht gezogen werden, die in der Literatur hinreichend belegt sind, die am einfachsten anzugehen sind, die am dringendsten eine Änderung der klimaschädlichen Praktiken erfordern, die das größte Einsparpotenzial haben und die durch gemeinsame internationale Anstrengungen unterstützt werden können. Da die natürlichen, sozialen und wirtschaftlichen Bedingungen in den verschiedenen Regionen sehr unterschiedlich sind, müssen alle Maßnahmen zur Verbesserung der Klimaschutzmaßnahmen im Agrarsektor sorgfältig auf die nationalen oder regionalen Bedürfnisse und Umstände zugeschnitten werden.

Um die Nahrungsmittelversorgung im Zusammenhang mit den Folgen des russischen Krieges gegen die Ukraine sicherzustellen, müssen preissteigernde Exportbeschränkungen durch große Agrarländer verhindert und freier Handel gewährleistet werden (Rudloff und Götz 2022). Gleichzeitig besteht die Gefahr, dass die jüngsten Reaktionen der EU und der USA, Maßnahmen zum Naturschutz auszusetzen und die Gesetzgebung zum Naturschutz und zur Regulierung von Pestiziden zu verschieben, weiteren Druck auf die natürlichen Ressourcen und die biologische Vielfalt ausüben (Rudloff und Götz 2022; Die Grünen/EFA 2022). Es ist heute wichtiger denn je, Strategien zu verfolgen, um die Ernährungssicherheit mit dem Kampf gegen den Klimawandel und die Erosion der biologischen Vielfalt auf globaler und nationaler Ebene in Einklang zu bringen, um in Zukunft ein nachhaltigeres Ernährungssystem für alle zu erreichen.

Die Aufnahme von Minderungszielen für die Landwirtschaft in die NDCs der Länder bietet die Möglichkeit, verstärkte Anstrengungen zu unternehmen, um die Emissionen aus der Ernährung zu senken. Bislang konzentrieren sich die NDCs häufig auf Aspekte der Lebensmittelproduktion und lassen nachfrageseitige Maßnahmen zur Förderung von Ernährungsumstellungen und zur Bekämpfung der Lebensmittelverschwendung außer Acht. Eine stärkere Einbindung aller relevanten Stakeholder in die NDC-Entwicklungsprozesse und die Ausrichtung der Agrarförderung und anderer politischer Maßnahmen auf den Klimaschutz kann dazu beitragen, den NDC-Prozess zur Förderung von Minderungsmaßnahmen im Agrarsektor zu nutzen (Global Alliance for the Future of Food 2022).

Es gibt Möglichkeiten, die Emissionen aus der Landwirtschaft zu verringern und gleichzeitig die Ernährungssicherheit zu verbessern. Um eine nachhaltige Umgestaltung unseres Lebensmittelsystems zu erreichen, müssen wir unseren Ansatz und unsere Einstellung zur Landwirtschaft überdenken, anstatt uns nur auf technische Lösungen zu konzentrieren. Dazu ist das Engagement von Regierungen, Unternehmen, Erzeugern und Verbrauchern* Verbraucherinnen erforderlich, unterstützt durch eine international abgestimmte Agenda.

# 1 Introduction

Global warming is threatening our ecosystems and livelihoods. Reducing greenhouse gas emissions is a prerequisite to limit climate change and keeping our planet liveable. Food systems are the basis of our survival, but they are also part of the problem. The IPCC Special Report on Climate Change and Land Use estimates that a fifth to a third (21-37%) of global GHG emissions are attributable to our food systems: 9-14% is caused by crop production and livestock on farms, 5-14% by land use, and 5-10% by the food production value chain (IPCC 2019b, p. 58). In addition to being a source of greenhouse gases, the intensification of agriculture and the trend towards large-scale monocultures are major drivers of biodiversity loss and pressures on water resources. The pressure on ecosystems is increased particularly by the high and increasing consumption of animal products. There is a decline in productive agricultural land due to climate change and infrastructure expansion (Chen et al. 2020; IPCC 2019a). Without a shift to diets that are predominantly plant-based and the implementation of further mitigation measures it will be impossible to meet the goals of the Paris Agreement and to keep the environmental effects of the food system within planetary boundaries (Clark et al. 2020; Willett et al. 2019; Springmann et al. 2018).

At the same time, the agricultural sector[3] is responsible for providing sufficient, nutrient-rich food and thus plays a key role in achieving the Global Sustainable Development Goals (SDGs). The growing world population increases the demand for food and other biogenic resources from agriculture and forestry. Until 2050, global food demand is projected to increase by more than 50% compared to 2010 (WRI 2019). According to WRI (2019), emissions from agricultural production need to be reduced by close to 40% together with carbon removals through large-scale reforestation in order to achieve net-zero emissions from the land sector in 2050 while providing food to an increasing world population. Recent developments in the context of Russia’s invasion of Ukraine, particularly sharp price increases for wheat and fertilisers as well as disruptions of supply chains particularly for Northern Africa, Asia and the Middle East, are posing additional threats to global food security (Dongyu 2022; Kurdi et al. 2022).

Agriculture provides the economic livelihood for many people, especially in countries of the global South. An increase in agricultural productivity correlating with economic growth in the agricultural sector has a great potential for poverty alleviation if the extra income is spent locally (World Bank 2007). GDP growth in agriculture has shown to be considerably more effective in poverty alleviation than growth resulting from non-agricultural activities (OECD 2010; Christiaensen et al. 2011).

Yet, the agricultural sector is suffering the impacts of global warming, with far-reaching ecological, economic and social consequences. Global warming and changing amounts of precipitation can lead to reduced crop yields or even crop failure, posing a threat to the livelihoods of large numbers of people in rural areas and affecting food supplies (FAO 2019b). Many cost-effective options for mitigating greenhouse gas emissions in agriculture have been identified, which often also contribute to climate adaptation or food security. The great synergies between mitigation and adaptation in land use can lead to positive co-benefits and lower costs. Furthermore, mitigation and conservation goals need to be addressed together: land adaptation contributes to halting biodiversity loss, and conversely, biodiversity conservation and restoration contribute to successful land adaptation. Making the agricultural system more

[3] For the scope of this report, “agricultural sector” refers to the whole economic sector, while a focus is put on mitigation measures that can be implemented at farm level. Unless specified otherwise, the sector is considered at global level.

sustainable thus involves two key priorities: preserving the environment and providing "safe and healthy food for all" (IUCN 2020).

To contribute to these goals, sustainable agriculture[4] needs to take into account environmental, social and economic sustainability as the central pillars of sustainable development (Larbodière et al. 2020). Discussed in various studies, the principles of sustainable agriculture can be summarised as efficient resource use, avoiding unnecessary use of external inputs, harnessing agroecological principles and building on nature's capacities for self-restoration, protecting natural ecosystems, and implying benefits for social development (see e.g. Pretty and Bharucha 2014; FAO 2014; Trigo et al. 2021).[5]

In this report, we analyse a diverse range of mitigation options to make agriculture and the broader global food system more sustainable.[6] For the agricultural sector, a technical mitigation potential of up to 9.6 Gt $CO_2e$/year on the supply side from crop and livestock activities and agroforestry and up to 8.0 Gt $CO_2e$/year on the demand side from dietary changes by 2050 has been identified. The economic mitigation potential is estimated at up to 4.0 Gt $CO_2e$/year from crop and livestock activities on the supply side by 2030 and up to 3.4 Gt $CO_2e$/year on the demand side by 2050 at prices of 20-100 USD $tCO_2$ (IPCC 2019c). Yet, barriers at the institutional, political, financial, socio-cultural, technical, or biophysical levels obstruct their implementation.

On the basis of a literature review, this paper outlines the main mitigation options for agricultural activities and the broader food system as well as barriers for implementing these options (Chapter 2).[7] We put a focus on measures to mitigate emissions or to increase carbon sequestration in natural sinks. On the supply side, we focus on those options that are directly associated with agricultural practices and can be implemented at farm level, comprising the preparation and management of land, the crop choice and diversity, technologies employed as well as the harvesting process. Energy use in the agricultural sector and the production of fertiliser as mitigation options that are related to the broader agricultural system but not on-farm measures are briefly outlined. On the demand side, we include measures that directly impact agricultural production. The subsequent stages of transporting, distributing, processing and retailing agricultural goods was consciously not part of the analysis. Chapter 3 clusters the identified barriers. In Chapter 4, policy recommendations to overcome the identified barriers are outlined.

As agricultural systems are highly diverse and specific to local circumstances, there is no single approach to mitigating emissions from these systems and shift them to more sustainable practices that will fit all contexts (Pretty and Bharucha 2014). Likewise, barriers to implementing mitigation options are context-specific and local actors will know best how to

[4] Different terms are used to describe approaches towards more sustainable agriculture, including agroecology, conservation agriculture, carbon farming, circular agriculture or climate smart agriculture. These terms imply different scopes of activities covered as well as different principles, goals and means for a transformation of the agricultural system (IUCN 2020; Verhagen et al. 2017).

[5] Recently, the concept of 'Nature-based Solutions' (NbS) has received broad public attention which can further help to delineate sustainable approaches to agriculture. Defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN 2016), the term indicates that through a provision of ecosystem services nature can provide solutions to societal challenges such as climate mitigation and adaptation (Oeko-Institut; Ecologic Institut 2022). For croplands, Griscom et al. (2017) have outlined a number of measures with climate mitigation potential that are considered as "natural climate solutions".

[6] We discuss for the mitigation options covered, to what extent they fulfil the requirements of sustainable agriculture. Options with side-effects that clearly contradict the stated principles, for example the genetic manipulation of crops or species, are excluded from the analysis.

[7] As part of the research project, papers analysing mitigation options and barriers will be prepared for ten selected countries (Argentina, Australia, Brazil, China, Egypt, Indonesia, New Zealand, South Africa, the UK and the USA) which will be informed by the analyses of this paper.

overcome existing challenges. Suitable pathways for the sustainable development of food systems will combine improvements in technologies and management, reductions in food loss and waste, and dietary changes in a way that pays attention to local contexts and environmental pressures (Springmann et al. 2018).

# 2 Mitigation options for the agricultural sector

To mitigate emissions from agricultural processes, many cost-effective options for mitigation have been identified, which often also contribute to climate adaptation or food security (IPCC 2019b).

In the following sections, the main options to enhance mitigation in the agricultural sector are outlined and the main barriers impeding their implementation are identified.

## 2.1 Supply side measures

Emissions related to the global food system comprise emissions generated at the farm level through agricultural practices, emissions from energy use for agricultural activities (see box below), emissions from the supply chain (transportation, storage and processing of food as well as food waste and losses throughout the supply chain) as well as emissions at the demand side related to the consumption of food, including dietary habits and food waste by consumers (Clark et al. 2020).

**Energy use for agriculture**

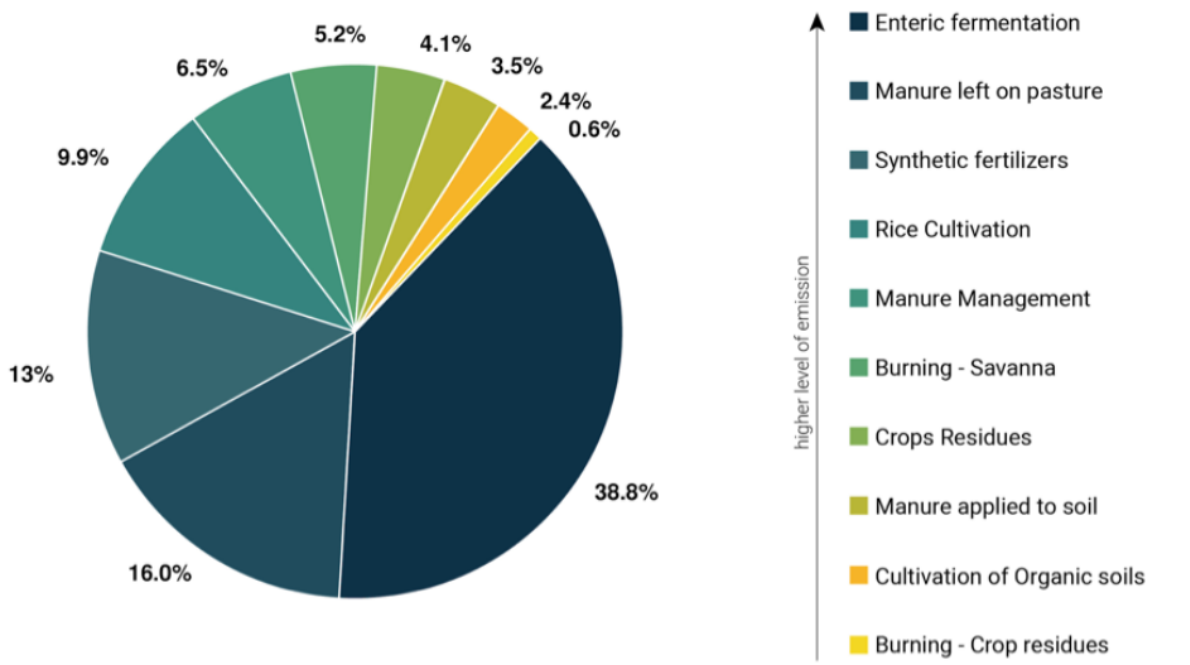
Approximately 15-30% of the primary energy consumption is used for the global food system. This energy amounts to around 80-160 EJ/year (EJ=exajoule=$10^{18}$ joules, the large range results from the diversity of farm to table systems worldwide) and depends mostly on the use of fossil fuels (Schramski et al. 2020). The emissions related to energy use and electricity are about 1029 Mt $CO_2e$/year with an increase of 7% from 1990 (Flammini et al. 2022). A large share - almost half of the estimated emissions - arise from combustion of fossil fuels and electricity generation for field machinery and on-farm irrigation. Burning gas and diesel oil is the largest source of on-farm $CO_2$ emissions.

Trends vary between different continents: In Europe, emissions decreased from 410 in 1990 to 145 Mt $CO_2e$/year in 2019. This is due to the fact that less energy was consumed by primary production in absolute terms and there has been a shift to cleaner energy carriers, thus decreasing the overall agricultural GHG intensity (Flammini et al. 2022). The pace of shifting energy used in agriculture to renewable sources has been very slow with an increase of the share of 5 to 10% in the EU between 2004 and 2018 (Gołasa et al. 2021). In Asia, emissions related to energy use in agriculture increased from 380 in 1990 to 629 Mt $CO_2e$/year in 2019 (Flammini et al. 2022).

While emissions from energy use in agriculture only make up about one fifth of the total GHG emissions arising from crop and livestock production, they are a significant source of $CO_2$ in the sector (Tubiello et al. 2021). Lower energy use and improved energy efficiency are important to mitigate emissions related to agriculture. Better management of resources with data informatics or artificial intelligence could help to reduce emissions but can also imply a higher energy use (Schramski et al. 2020). The deployment of different types of renewable energy in rural areas and transforming farms into a producer and consumer of energy could also be part of mitigation measures (Gołasa et al. 2021).

Globally, the three main emission sources from agricultural activities at the farm level are enteric fermentation, manure on pasturelands and the use of synthetic fertilisers, jointly accounting for over 65% of emissions in the sector:

**Figure 1: Share of total emissions caused by the agricultural sector by farming activity**




Notes: Emissions are based on countries' GHG inventories as submitted to the UNFCCC. As a result of incomplete reporting, significant data gaps exist for non-Annex I countries.

Source: Thissen 2020 on the basis of FAO 2020a

In the following sections, we focus on mitigation measures on the supply side and barriers that obstruct their implementation at farm level. The mitigation options considered include changing the intensity of cultivation (section 2.1.1), the improved management of nitrogen fertilisers (section 2.1.2), improved management of livestock manure (section 2.1.3), reduced emissions from livestock (section 2.1.4), carbon storage in agricultural systems (section 2.1.5), reduction of emissions from rice cultivation (section 2.1.6) and burning practices (section 2.1.7).

### 2.1.1 Changing the intensity of cultivation

Global land use change has been a major driver for climate change. Particularly, global deforestation driven by agricultural expansion has contributed substantially to GHG emissions from the land-use sector (see chapter 2.2.3) (Winkler et al. 2021). In order to reduce emissions from agriculture, the intensity of agricultural production needs to be considered. Consciously changing the intensity of cultivation practices may imply multiple environmental benefits, ranging from reduced emissions to healthier soils, enhanced biodiversity and positive impacts on livelihoods.

The global picture is complex: "Conventional intensification" of agriculture in the form of large-scale industry-driven monocultures causes enormous environmental damage. Moreover, contemporary food usage is inefficient with about one third being wasted and another third being used to feed livestock (see chapter 2.2.1 and 2.2.2). At the same time, smallholder farming is the backbone of global food security (Tscharntke et al. 2012) which was not guaranteed for about 12% of the world's population or 928 million people in 2020 (FAO et al. 2021).

The extensification of crop production (i.e. decreasing the use of capital and inputs per land area) can contribute to reducing emissions from agriculture and making production more environmentally sustainable. This can be done by using land less intensively, providing time for fallows and recovery of the soil in between production cycles. Extensification can lead to higher local diversity and less environmental pollution but will require a larger area of land. It can be an appropriate strategy in affluent regions if combined with adjusted diets that reduce global land demand and if environmental costs are reflected in food prices (van Grinsven et al. 2015).

Extensifying agricultural production can reduce the amount of food produced or imply changes to the crops that are produced. In smallholder contexts in the global South, sustainable agricultural practices may therefore imply a "sustainable intensification" of agriculture. "Sustainable intensification" is defined as a process or system "where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land" (Pretty and Bharucha 2014; Oberč and Arroyo Schnell 2020; Godfray et al. 2010). Sustainable intensification is an opportunity and a necessity to shift the agricultural sector from being the world's single largest driver of environmental change to becoming a key contributor to global sustainability and human prosperity (Rockström et al. 2017). In the context of smallholder farming, intensification may also lead to an expansion of agricultural production at landscape level (Michalscheck et al. 2020; Ceddia and Zepharovich 2017; Weller von Ahlefeld 2020; Pellegrini and Fernández 2018).[8] If a farmer successfully cultivates a highly productive small piece of land, he/she will want to expand production in order to sell the surplus so that ultimately more land is used. Pressure to nourish a growing population has also led to a shortening of fallow periods in the global South e.g. in Ghana (Codjoe and Bilsborrow 2011) and 'unused' land bears the risk to be lost to other farmers or to be settled (Goldstein and Udry 2008).

**Mitigation approaches**

Concrete approaches/options for sustainable cultivation include (see also IPCC 2019b, p. 60):

- Increasing crop variety in order to conserve nutrients in the soil from one season to the next and interrupt the life cycles of insect pests, diseases and weeds through e.g. cultivation of legumes; enhancing crop sequencing and perennial farming and other measures to improve the soil structure and enhance organic matter (see also Chapter 2.1.5), which is often referred to as "conservation agriculture" (Vanlauwe et al. 2014; Minasny et al. 2017; Oberč and Arroyo Schnell 2020). According to Griscom et al. (2017), a technical mitigation potential of up to 0.4 Gt $CO_2$e/year could be achieved in 2030 through conservation agriculture.
- Agroforestry: growing trees on agricultural land or cultivating crops in forests to enhance yields from staple food crops, increase biodiversity, and enhance carbon sequestration while at the same time enhancing farmer livelihoods. Additionally, agroforestry supplies input of organic material from trees. Using nitrogen-fixing trees, in e.g. improved fallows, adds high amounts of nitrogen to the soil which can reduce the need for inorganic nitrogen fertilisers (Akinnifesi et al. 2010). Trees also provide shade to the crops and improve water storage in soils, thus protecting croplands against the impacts of climate change and improving soil structure and health. By withdrawing water from a large soil volume, trees can grow and produce food even during long lasting droughts. Agroforestry systems also occupy more ecological niches and can use the available water more efficiently (Kay et al. 2019; Kim et al. 2016). Furthermore, agroforestry can reduce illegal logging of forests for energy purposes

[8] It is important to note though that traditional farming methods often imply practices that sequester carbon, e.g. by minimising soil disturbances, diversifying crops and planting legumes, perennials or cover crops; yet these more sustainable approaches to agriculture particularly in Black and indigenous communities have been marginalised and excluded from access to capital and public subsidies ((van der Pol 2021)).

by providing fuel wood. On average, agroforestry systems are estimated to annually capture 27 tonnes of $CO_2$ equivalents per hectare (Kim et al. 2016). Griscom et al. (2017) estimate the mitigation potential of agroforestry at 1.0 Gt $CO_2$e/year by 2030.

- Increasing fallow land if sufficient cropland is available and does not interfere with, for example, biodiversity objectives, allowing for land rehabilitation of unproductive areas, or even afforest cropland where it is not needed to ensure food security. [9]
- Combined crop-livestock systems allowing for optimal nutrient recycling and integrated nutrient management, reducing the need for chemical fertilisers (Oberč and Arroyo Schnell 2020).
- Extensive grassland use through rotational farming systems to reduce greenhouse gas emissions of livestock, enable healthy grasslands and increase animal welfare (Pretty and Bharucha 2014). However, it depends on local circumstances and the overall amount of animals held (see also section 2.2.2) to what extent this extensive form of farming can be considered sustainable (Oberč and Arroyo Schnell 2020).
- The integrated management of nutrients forms part of several strategies to sustainably change the intensity of agricultural production. In closed nutrient cycles, nutrients in a farm system are recycled by using on-farm manure on fields, using crops that conserve the nutrients in soils and using agricultural residues as inputs for animal feed or for energy production (see also section 2.1.5) (IUCN 2020).
- Changing conventional agriculture to organic agriculture. The success and feasibility of organic farming strongly depends upon local conditions, such as the availability of organic material and labour. Additionally, organic agriculture may need more land to generate the same yield, which raises questions about its scalability (Oberč and Arroyo Schnell 2020; Verhagen et al. 2017, p. 11). Organic agriculture is so far the only legally defined approach for sustainable agriculture (Oberč and Arroyo Schnell 2020). It can lead to increased SOC stocks in agricultural soils (Gattinger et al. 2012) as well as on grasslands, decreases the need for synthetic fertilisers, contributes to reducing food waste and provides additional environmental co-benefits related to biodiversity, adaptation to climate change and eutrophication (Müller et al. 2016).

**Mitigation potential**

Quantifying the mitigation potential of measures for sustainable cultivation is challenging. The measurement and monitoring of soil organic carbon to produce reliable estimates at a country level is particularly difficult and linked to large uncertainties. GHG fluxes as well as carbon stocks in soils are spatially variable and heterogeneous as they are determined by climate impacts, soil characteristics as well as management practices. All of these factors interact with each other and are still poorly quantified (Bispo et al. 2017; Paustian et al. 2016). Further uncertainties are related to the reflection of management activities in the estimation and the management-related stock change factors. The complexities of the interactions between all drivers and the development of different stability fractions of soil carbon are not yet fully understood, and simplified assumptions and stock change factors are often used which are

[9] In the debate around sustainable intensification, some studies have looked into the potential of technical optimisation of agricultural practices and crop reallocation. Folberth et al. (2020) estimate that technically, optimising fertiliser inputs and global optimal crop reallocation would reduce the cropland area required to maintain present production volumes by almost 50%. However, in practice this would have major socio-economic impacts on livelihoods and increase the reliance on food imports. Additionally, optimising cropland distribution based on land use efficiency could result in monocultures with negative environmental impacts.

related to additional uncertainties. Frequently, exact annual data sources for management practices with a country-level mapping are missing. An example is the incorporation of crop residues that is often estimated based on the crop types. However, the information on the cultivated crops does not necessarily provide correct information regarding whether the residues are incorporated into the soils or whether they have been burnt or collected for other uses (e.g. anaerobic digesters). Another example are different tillage intensities (ploughing, minimal tillage or no tillage) that are not collected and mapped annually in many countries. Some management practices can be detected through remote sensing methods, but practices such as different tillage methods require additional data collected from farmers to reduce the uncertainties related to the estimation of management impacts.

#### Barriers for the implementation of mitigation options

The implementation of such mitigation options will strongly depend on the local conditions. Firstly, a **lack of knowledge** on alternative cultivation practices may obstruct changes. **Socio-cultural barriers** play an important role because changes to agricultural practices are not always easy to implement and personal attitudes or cultural traditions might impede a change of practice (OECD 2017; Mills et al. 2020). For example, shifts in farm practices may affect different members of a (smallholder) farm differently: legumes may have to be harvested by the women, while other crops may only be planted or harvested by men. This is aggravated if **institutional support or advice from public or private locally accessible actors is missing** (Mills et al. 2020). Particularly in smallholder contexts, quality seeds to implement a reliable crop diversification or equipment like tractors for ploughing or weather forecasts for planting might not be available without targeted support. Further **economic barriers** are created by the fact that some strategies for sustainable intensification, such as agroforestry systems, are long-term strategies. For farmers, economic planning will be difficult if year-to-year harvests are not secure as it will take time for the trees to grow.

**Tenure and land use rights** might pose barriers to changing agricultural practices as well. Determining the right incentives and approaches to agricultural production will be highly dependent on local contexts and require a high level of expertise by local practitioners who have identified small-scale solutions to deal with ecosystem diversity for food production.

Additionally, there is a **lack of goal or vision of sustainable agriculture** preventing coherent political incentives for sustainable practices (Oberč and Arroyo Schnell 2020). **Common metrics and indicators to measure the benefits of sustainable approaches to the intensity of cultivation are missing** (IUCN 2020) and a market for organic products is lacking (Oberč and Arroyo Schnell 2020). Regulations and labelling associated with organic agriculture can create barriers for farmers to change their practices (Oberč and Arroyo Schnell 2020). As long as more revenues are generated with conventional, intensive, monocrop-cultivation, many agricultural businesses or industrial farmers do not have an incentive to change towards greater diversity and extensive systems, that might have advantages in the long term. Currently, **negative externalities caused by large scale mono-cropping or intensive animal husbandry are largely not accounted for**. Continuous investments into infrastructure for an intensive crop cultivation or animal husbandry may create a **lock-in effect** into outdated and unsustainable farm practices, hindering a change process even if knowledge base or incentives change (Frison 2020).

#### Recommendations for overcoming barriers

<u>Awareness-raising and capacity building</u>

At (small-scale) farm level, the benefits from changing agricultural practices need to be emphasised. Capacity building is needed to disseminate information e.g. particularly through farmer field schools[10], with demonstration plots where farmers actively engage, can help overcoming the unfamiliarity of new approaches as well as the high risk perception (e.g. N2 Africa[11]) (ODI Agricultural Research & Extension Network 2000). Other approaches of peer-to-peer learning include identifying so-called 'lighthouse farms', i.e. farms that are considered best-practice examples.[12] These can inspire other farmers as well as agricultural businesses to make a shift towards a more sustainable production on their own land. Small-scale farmers can (often) only make large technology changes if they form groups (often called: farmer-based organisations (FBOs)) (GIZ 2016; Abdul-Rahaman and Abdulai 2022).

Financial support

Microfinancing (or farmer savings groups) may help farmers to access funds if investments are needed for changes in farming practices. Farmers should be enabled to access and afford the inputs they need to make optimal use of their land resources. For example, in sub-Sahara Africa, organic resources are lacking which would be necessary to increase crop yields under minimal tillage. In such contexts, promoting access to sustainable input supply chains for fertilisers at appropriate prices can substantially increase crop productivity and organic residue availability in smallholder farms and thus contribute to a sustainable intensification of agriculture (Vanlauwe et al. 2014).

Policies and regulations

On a governmental level, public support needs to be redirected to focus on sustainable practices (World Bank 2020; Climate Focus; CEA 2014; FAO and UNDP 2021; Mills et al. 2020). On the level of local or sub-national policy-making it needs to be made clear how food security consists not just of calories, but of nutritional diversity, i.e. a greater diversity in crops grown. In many countries in Africa, Asia, South America but also across developed countries, schools offer meals that are government-subsidised. Procurement in various public institutions could put a focus on locally produced, diverse and organic food, resulting in less food waste because of shorter supply chains and increased implementation of sustainable practices. That way, a stable market and demand can be supported, which influences what farmers grow (e.g. more legumes and vegetables).

Research and development

Additionally, more work is needed to foster the setting of common metrics and indicators to measure the benefits of approaches for sustainably changing the intensity of agricultural production (Oberč and Arroyo Schnell 2020). Otherwise, it will be difficult to monitor progress and uptake of changed land use intensity.

### 2.1.2 Improved management of nitrogen fertilisers

The AFOLU sector is the primary anthropogenic source of $N_2O$, which is mainly attributed to the application of nitrogen as a soil fertiliser. However, around 50% of the nitrogen applied to agricultural land is not absorbed by crops (WRI 2019). A mismatch in timing of nitrogen application with crops needs is the greatest contribution to the large magnitude of nitrogen loss (Robertson and Vitousek 2009).

In regions where application rates are high and exceed crop demands for parts of the growing season, decreasing or optimising the use of nitrogen fertiliser would have large effects

[10] See e.g. https://www.fao.org/farmer-field-schools/home/en/.

[11] See https://n2africa.org/improved-early-education-n2africa-style.

[12] See https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Farming-Systems-Ecology-Group/Lighthouse-project.htm.

on emission reductions (IPCC 2019b p.46). Substituting synthetic fertiliser for organic fertilisers, such as compost or manure, and incorporating nitrification inhibitors into fertiliser are additional nitrogen management measures that can contribute to emission reductions.

Nitrogen fertilisers are responsible for meeting half of the world's food demand (Erisman et al. 2008), so it is crucial for fertiliser use to be reduced without compromising crop yields.

**Mitigation approaches**

The following approaches are available to improve the management of nitrogen fertilisers:

- **Applying management principles such as the 4Rs** can reduce excess nitrogen loss, and as a result, nitrogen oxide emissions. The 4Rs approach consists of using the right nutrient source, at the right rate, right time, and in the right place to optimise crop yields while minimising nutrient loss (IFA et al. 2016). It is a site-specific process relying on the scientific principles of fertilising while considering climactic and soil conditions, crop types, and management systems (ibid).

- **Precision farming** tools with high-tech equipment can aid farmers in monitoring nitrogen inputs and implementing the 4Rs management approach. Technologies like Variable Rate Nutrient Application (VRNA) can adjust fertiliser application according to crop needs, which is based on real-time data from canopy sensors (Balafoutis et al. 2017). Using VRNA technology can reduce fertiliser overapplication while improving agricultural productivity and crop quality (ibid). The environmental and economic benefits of VRNA can be compounded if using manure in place of synthetic fertiliser.

- **Organic fertilisers**, such as compost and manure, can replace the use of synthetic fertiliser on farms. Using compost decreases the extent of nitrogen leaching and loss, and reduces the demand for synthetic fertiliser, decreasing the emissions associated with its manufacturing, transportation, and application (Favoino and Hogg 2008). Applying manure in place of fertiliser has the potential to reduce GHG emissions, but if mismanaged, can instead increase $N_2O$ and $CO_2$ emissions from soil (Snyder et al. 2014). However, combining manure and synthetic fertiliser can decrease the latter's application rate by 10% (ibid). Biochar is not a direct substitute for fertiliser but can be applied to crops to reduce the need for synthetic fertilisers (Filiberto and Gaunt 2013), while also reducing $N_2O$ emissions by inhibiting the nitrification process (Cayuela et al. 2013). However, the effects of biochar on emissions need to be critically assessed through a more comprehensive life-cycle assessment as in most cases, no excess biomass is available for which the production of biochar would be the most sustainable use. Additionally, the application of biochar can have negative effects on soil health (see section 2.1.5).

- **Nitrification inhibitors** are a technical measure that can reduce the extent of ammonia that undergoes biological oxidation and is converted to nitrate. Nitrate is highly mobile and prone to loss via leaching or conversion into gaseous N forms, including $N_2O$, if the nitrification process goes rapid and unchecked (Subbarao et al. 2012). Only 2% of global fertiliser use includes nitrification inhibitors (WRI 2018 p.48). Other technologies that similarly rely on keeping nitrogen fixed in the soil include slow-release fertilisers, enhanced efficiency fertilisers, and urease inhibitors (Snyder et al. 2014). However, synthetic nitrification inhibitors are synthetic chemicals applied as external inputs and can have negative effects on soil as biodiversity as they can be ecotoxic for terrestrial and aquatic organisms (Kösler et al. 2019) as well as imply risks to human health (Ray et al. 2021).

- **Nitrogen use efficiency** (NUE) is a crucial concept when considering fertiliser management. It refers to the "percentage of nitrogen that is absorbed by crops rather than lost to the environment" (WRI 2018 p.48). NUE values vary greatly by country, individual farm and crop type. For example, fruits and vegetables have an extremely low average NUE of 14% (Zhang et al. 2015). The current global average for NUE is 42% (ibid). NUE can be improved by measures such as the 4Rs approach to fertiliser application, precision agriculture, and employing nitrification inhibitors (Zhang et al. 2015).

Excessive nitrogen fertiliser application poses threats to ecosystem and human health. Its potential consequences include soil and freshwater acidification, eutrophication and the creation of marine dead zones, air pollution, and groundwater contamination (Vries et al. 2013). Due to changes in soil pH, toxicity, and nutrient overload, the accumulation of nitrogen also drives terrestrial biodiversity loss (Bobbink et al. 2010). Thus, reducing nitrogen overapplication provides several benefits in addition to reduced GHG emissions.

#### Mitigation potential

The IPCC estimates the mitigation potential for improved nitrogen fertiliser management to be between 0.03 and 0.71 Gt $CO_2$e/year based on technical feasibility and assuming a 30% decrease in synthetic fertiliser emissions (IPCC 2019b, p. 48; Roe et al. 2019).

New technologies that reduce fertiliser overapplication, such as VRNA, can reduce the baseline GHG emissions rate by up to 10% (Balafoutis et al. 2017). By applying fertilisers and pesticides only where they are needed, precision farming can also benefit the environment by reducing the development of pesticide resistances. Yet, more research on the precise environmental impacts of precision farming is required as most studies only indirectly estimate the environmental benefits by measuring the reduced chemical loading (Bongiovanni and Lowenberg-Deboer 2004). Additionally, required technologies are not available or too expensive for many contexts of smallholder agriculture, and employing these technologies requires powering of additional data centres, which will increase energy consumption (Oberč and Arroyo Schnell 2020).

Incorporating nitrification inhibitors can reduce $N_2O$ emissions by 31-44% compared to conventional fertilisers (Akiyama et al. 2010). Regarding nitrogen use efficiency, the WRI estimates that reaching a global average NUE of 71% would reduce nitrogen emissions by 0.6 Gt $N_2O$ (WRI 2018 p.48).

#### Barriers for the implementation of mitigation options

Nutrients derived from chemical fertiliser application dominate in the global North, along with parts of China and India, while manure nutrient availability is greater than synthetic fertiliser application in the global South (Potter et al. 2010). Manure is an abundant and cheap alternative to synthetic fertiliser. However, its transportation and application to the field is quite labour-intensive. For this reason, the ability to afford high fertiliser prices discourages manure use (Ketema and Bauer 2011).

Global hotspots for nitrogen fertiliser use include China, India, the U.S., Brazil and Pakistan, who together accounted for 63% of nitrogen fertiliser consumption in 2013 (Lu and Tian 2017). Overuse of synthetic fertilisers is especially common in China, where most farmers could reduce their nitrogen fertiliser application rates by 30-60% without experiencing a loss in yields (Ju et al. 2009).

On a global scale, **farm size affects the extent of fertiliser overapplication**. Smallholders that do not have much land are significantly less likely to compromise potential crop yields by reducing fertiliser use. They also use more labour-intensive practices rather than investing in machinery or technology that optimises the fertiliser application process (Ju et al. 2016). This problem is exacerbated by **insecure land tenure**, since short-term leases on land parcels disincentivise farmers from investing in alternative fertiliser application practices with long-term benefits (Viaene et al. 2016).

**Subsidies for synthetic fertilisers** significantly impact farmer's decisions on how much and which kind of fertiliser to apply. Between 2014 and 2016, synthetic fertilisers were responsible for around 10 Mt $CO_2e$ of global GHG emissions (Laborde et al. 2021). Similarly, crop subsidy payments based on the extent of production perversely promote fertiliser overapplication (Robertson and Vitousek 2009). The high price of compost currently disincentivises its large-scale use. On-farm composting has high upfront costs due to the technology investments required, while purchasing alternative fertilisers (including manure) is associated with high transport costs (Viaene et al. 2016; Zhang et al. 2021). These economic barriers could be alleviated by outsourcing compost production to a service provider, thus limiting the investments needed from farmers, or by providing a financial stimulus to compensate for high costs (Viaene et al. 2016).

**The NUE potential and best fertiliser management practices on farms is highly variable** based on the soil type and crop type. This makes it difficult to apply a 'one size fits all' solution when it comes to fertiliser management (Venterea et al. 2012). Environmental factors also play a role in the extent of nitrogen emissions from organic fertilisers (Kitamura et al. 2021). As a result, prescribing solutions on an individual farm level requires extensive resources and knowledge on key nitrogen uptake processes.

Studies ranging from India (Pandey and Diwan 2018) to the United States (Stuart et al. 2013) cite a **lack of capacity building efforts** as a significant barrier to adopting new management practices. Many farmers have not made the connection between fertiliser application and climate change, and usually receive their recommendations from fertiliser dealers rather than scientists and extension offices (Stuart et al. 2013). In South Asia, most farmers are not aware of scientific recommendations and apply fertiliser to their discretion based on what is affordable and available (Aryal et al. 2021).

Most producers apply more fertiliser than is required for optimum yields, since this minimises their perceived economic risks (Robertson and Vitousek 2009). **Risk aversion is a significant social barrier** to reducing fertiliser overapplication.

#### Recommendations for overcoming barriers

<u>Awareness raising and capacity building</u>

Stakeholder engagement is a crucial approach to improve nitrogen fertiliser management, especially in countries or regions dominated by smallholder farms. Local recommendations based on agroecological zones must be developed due to the high variability of soil and crop types. That information can be deployed via coordinated campaigns that engage farmers across the country. In China, this approach increased average yields of grains by 10.8-11.5% and decreased nitrogen application by 14.7-18.1% over 37.7 million hectares (Cui et al. 2018).

<u>Financial support</u>

Paying farmers the yield difference between an overfertilised strip and the larger portion of the field fertilised at the recommended optimum rate can alleviate the perceived financial risk of under-fertilising and reduce excessive nitrogen fertiliser application (Robertson and Vitousek 2009). Financial incentives such as green payments based on ecosystem services can further reduce emissions resulting from fertiliser application (ibid). Conservation funding should support projects that bring together producers with scientists to try out innovations regarding the reduction of fertiliser or pesticide use. Incentives to use fertiliser more efficiently are necessary in countries with currently high fertiliser use and alternatives to synthetic fertiliser should be promoted everywhere (Searchinger 2020). A tax or levy on nitrogen use can contribute to reducing nitrogen excesses in countries with high application rates (FÖS 2018).

**Production of fertiliser**

Around 85% of ammonia production is used to produce fertilisers. In total, ammonia production consumes 1.2% of global primary energy and contributes to 0.93% of global greenhouse gas emissions (Gonzalez-Diaz et al. 2020). Synthetic fertiliser production uses natural gas or coal both as a feedstock and as an energy input. China has the highest potential for reducing GHG emissions from improved fertiliser production due to the country's inefficient, outdated equipment and using coal as the primary feedstock (Climate Focus; CEA 2014). Although there are no global estimates, improving the efficiency of synthetic fertiliser production in China alone would mitigate emissions by 0.05-0.36 Gt $CO_2e$/year (IPCC 2019b; Roe et al. 2019). In general, shifting from plants with poor efficiency to production sites with the best available technology would improve energy efficiency by 25% and decrease GHG emissions by 30% (IFA 2009).

Current production processes rely on methane to generate hydrogen. Incorporating new carbon capture and storage (CCS) technologies in ammonia production plants can reduce emissions from production processes already considered efficient. A 90% capture level in all global ammonia plants can reduce emissions by 0.34 Gt $CO_2e$/year (Gonzalez-Diaz et al. 2020). However, implementing CCS technologies in the industrial sector is stunted due to their high costs and lack of economic incentives, and can increase natural gas consumption in the long run (The Royal Society 2020).

Using green hydrogen as an alternative feedstock and fuel can further reduce impacts from the ammonia production process but is quite costly (The Royal Society 2020). New technological innovations in urea production, such as selective electrocatalytic synthesis, can further improve the fertiliser production process by utilising renewable energy and environmental wastewater as feedstocks (Lv et al. 2021). The most significant **barrier towards incorporating better technologies is the sheer amount of time** that it would take to construct new plants or retrofit older ones and shift production processes, meaning several decades (IFA 2009).

While there is potential to reduce GHG emissions from improved fertiliser production, mitigation measures should focus on improving fertiliser management and reducing the extent of fertiliser applied on farms. The latter is more aligned with the principles of sustainable agriculture and conserving natural resources. The maximum emissions reduction potential for fertiliser management is also twice as large as that for fertiliser production, although the latter value focuses on the hotspot of China (IPCC 2019b; Roe et al. 2019).

### 2.1.3 Improved management of livestock manure

Livestock manure accounts for 35% of global nitrous oxide emissions as a result of manure being deposited on pastures by grazing animals, used as fertiliser on croplands, or stored in dry agricultural systems (Uwizeye et al. 2020). Manure stored in wet (anaerobic) systems also emits methane, accounting for approximately 5% of total global methane emissions (UNEP and CCAC 2021). Overall, manure from livestock accounts for roughly 25% of direct agricultural GHG emissions (Climate Focus; CEA 2014).

The type of livestock production system affects the extent of manure left on the pasture versus the extent that is managed. Grazing systems that are dominant in the global South contribute a significant amount of emissions from manure left on pasture, while industrialised systems predominant in the global North have sizable emissions from manure management (Climate Focus; CEA 2014). China, for example, has the fastest growing industrial livestock production system globally, but proper manure management practices have yet to be implemented (ibid).

**Mitigation approaches**

- Specific measures to reduce emissions released from livestock manure primarily consist of best management practices for storage or for application on soils. Measures related to manure deposited on grazing fields were not considered due to how disperse it is, making management challenging and unlikely. Manipulating diets can improve nitrogen utilisation by animals and reduce nitrogen excretion rates from manure (Samer 2015; Sajeev et al. 2018).
- Most manure is stored in "dry" systems, which accounts for 40% of total emissions from managed manure despite low emission rates. Emissions from "wet" systems can be up to 20 times higher per tonne of manure (WRI 2019). Incorporating techniques such as reduced storage time, covering the manure, and avoiding straw/hay bedding can greatly reduce emissions from stored manure (Climate Focus; CEA 2014).
- In addition to storage practices, manure utilisation has implications for greenhouse gas emissions. Digesters can convert manure into methane for energy use. However, this only results in a net emissions decrease if the manure is otherwise stored in wet form and methane leakage rates are low (WRI 2019).
- Manure can also be recycled and used as compost, or be partially substituted for synthetic fertiliser, provided it is combined with good practices for its application. Nitrogen is released during application, so the right time and technology are important. Manure application on soils can improve crop productivity, increase soil organic carbon storage, and potentially reduce the extent of nitrogen losses and subsequent nitrous oxide emissions compared to synthetic fertilisers (Xia et al. 2017). Integrated crop-livestock farming systems are one example of how manure application can enhance agricultural productivity and reduce the use of mineral fertilisers (Reddy 2016).

**Mitigation potential**

For most livestock systems worldwide, there is limited opportunity for manure management, treatment or storage; most excretion happens in the field and collection for fuel or fertility amendment occurs after it is dry and $CH_4$ emissions are negligible. Improving manure management has a technical mitigation potential between 0.01 and 0.26 Gt $CO_2$e/year (Roe et al. 2019).

There are greater opportunities for improved manure management in intensive or semi-intensive systems, where manure is more easily collected. There is potentially high mitigation potential, for instance, from improving the application of manure on the field. Shifting autumn manure application to spring and rapid incorporation of manure within 1 day of application (or even shorter) can reduce $N_2O$ emissions from manure applied to fields by 17% (Samer 2015). The total $N_2O$ mitigation potential from applying best practices ranges from 0.01 to 0.075 Gt $CO_2$e/year depending on the timing and form of application.

Improving manure management has several co-benefits in addition to greenhouse gas emissions reduction. Proper management can enhance food security by making better use of nutrients in manure as fertiliser and improving soil health, or it can be used as an energy source or basis for construction material (Wageningen University 2014).

Improper manure storage, including anaerobic lagoons, poses risks of water and soil pollution from acidification and eutrophication via nitrate and phosphorus leaching (Samer 2015). Incorporating proper manure application to soils in place of synthetic fertiliser can effectively reduce nutrient overload in bodies of water (Li et al. 2019).

Poor manure management can contribute to public health risks, such as the spread of waterborne diseases and odour generation, which can be mitigated by better storage techniques. Using manure as a source for energy generation can also improve public health by reducing black carbon emissions from open biomass burning, while providing cheap fuel for smallholders (Wageningen University 2014).

#### Barriers for the implementation of mitigation options

Policies and legislation regarding manure are often developed by multiple ministries, many of whom are not familiar with common farm practices. This leads to a **lack of coherent, complementary legislation** that is not aligned with current management practices and is seldom enforced (Wageningen University 2014). In general, there is a lack of policies that emphasise manure's value as fertiliser and its nutrient recycling potential.

**Financial barriers** play a large role in implementing improved manure management. **Limited access to subsidies and credits** for investing in infrastructure, machinery, and equipment with high implementation costs impedes adoption of best practices, especially for small farmers (ibid). Existing financial incentives often target anaerobic digester construction rather than the value of the output, which does not stimulate farmers to improve their manure management. **Subsidies for manure treatment techniques** are usually ineffective due to their high operational costs and technical failures (Tan et al. 2021). Likewise, replacing synthetic fertiliser with manure is disincentivised by existing fertiliser subsidies (ibid).

**A lack of awareness** is also cited as a key barrier towards implementing improved manure management (Wageningen University 2014). There is limited knowledge among stakeholders regarding the importance of sound manure management practices, its potential added value as fertiliser, and its co-benefits related to productivity and reduced environmental risks (ibid).

### Recommendations for overcoming barriers

Awareness raising and capacity building

Capacity building on the importance of integrated manure management for food security and emissions reduction is critical for the wider adoption of improved management practices. Better dissemination of information can alleviate the lack of knowledge and assist farmers in decision making (Wageningen University 2016). This outreach should also consider cultural aspects of manure and potential trade-offs of its utilisation, since using dung cakes for cooking is still a tradition in some regions (Wageningen University 2014).

Financial support

A greater extent of financial incentives and credits can improve access to the technology and labour needed for improved manure management. In the short-term, this means shifting subsidies from manure treatment techniques to manure-treated products, while implementing long-term support schemes to encourage investment in new treatment technologies (Wageningen University 2016; Tan et al. 2021). Phasing out synthetic fertiliser subsidies in favour of new markets for manure products can support the application of manure to soils. However, these financial incentives should be aligned with new, stricter regulations regarding manure management and manure markets to ensure uptake (ibid).

### 2.1.4 Reduced emissions from livestock

The livestock sector has major implications for natural resource consumption and livelihoods, and is responsible for approximately 16.5% of anthropogenic GHG emissions (Twine 2021). This number includes land use, but land use emissions from livestock are potentially underestimated (ibid). Ruminant animals, including cattle and sheep, emit methane as a by-product of digestion. Livestock methane emissions account for 32% of all anthropogenic methane emissions (UNEP and CCAC 2021). These enteric methane emissions from ruminant animals raised for their meat and milk can vary depending on factors such as feed quality, animal size, and environmental temperature. Improved grazing land management and higher-quality feed have high potentials for mitigation (FAO 2013a). Reducing the GHG emissions intensity per unit of livestock via these measures can support absolute emissions reductions, so long as total livestock production is limited (ibid).

#### Mitigation approaches

- Livestock feed optimisation (cattle): The composition of livestock feed can be optimised to reduce enteric fermentation. Feedstock optimisation is a longer-term process since determining the optimal feedstock for a specific region requires an iterative learning process on how local breeds of cattle respond to different locally available vegetation and grains (FAO 2013a; FAO 2013b).
- Breeding optimisation: The selective breeding of livestock can introduce species with higher productivity, resulting in lower emissions per unit of produce, or with reduced emissions from enteric fermentation (ibid).
- Health monitoring and disease prevention: To improve the productivity and GHG emissions per livestock unit, the genetic potential, reproductive performance, health, and liveweight gain of animals can be optimised through better herd management (Herrero et al. 2016).
- Grazing land management: Measures to manage grazing land including nutrient management, fire management, controlling grazing intensity and improving grass varieties can improve the carbon sink capacity of grazing soils and reduce the release of nitrous oxide (FAO 2013a).

It is important to note that measures that improve livestock productivity, while they reduce the emissions intensity, are generally associated with higher absolute emission levels due to the increased performance of livestock. These measures would only result in a decrease of absolute emissions if animal numbers were reduced in conjunction (FAO 2017).

The emissions impact from feed production includes land use change, fertiliser and pesticide production and application, agricultural operations, and feed processing and transport (Grossi et al. 2019).

#### Mitigation potential

In terms of mitigation potential, improving animal health and productivity could reduce livestock GHG emissions by 0.2 Gt $CO_2$e/year (Herrero et al. 2016). Reducing methane and nitrous oxide emissions from enteric fermentation and manure management by 40% in extensive, pasture-based systems in the global South and by 10% in intensive systems in the global North has the potential to mitigate between 0.12 and 1.18 Gt $CO_2$e/year (IPCC 2019b; Roe et al. 2019). If all livestock producers applied the production practices of 10% of producers with the lowest emission intensity, the sector's emissions could technically be reduced by 30%, or 1.8 Gt $CO_2$e based on available technologies and assuming a lack of adoption barriers (FAO 2013a).

Mitigation approaches to reducing livestock emissions can also provide co-benefits. A reduction in livestock numbers while maintaining the same level of output via productivity improvements could free up land that can be used for other purposes (FAO 2017). Livestock production is associated with land degradation, biodiversity loss, noxious emissions, as well as air, water, and land pollution (Opio et al. 2011). Thus, reducing the extent of pastureland would have positive implications for ecosystem and human health. Similarly, grazing management practices that reduce pressure on land improve soil health, biodiversity, and water quality, particularly when degraded grassland is restored (FAO 2013a). However, maintaining the same level of output requires more animal feed that must be grown on additional land, so the mitigation potential of such an approach is limited.

Livestock production has a strong link to rural livelihoods. Measures that improve productivity for smallholders could result in higher net economic returns, lower labour costs, increased regional development, and improved food security (Pereira et al. 2018). In addition, productivity measures such as improved health and disease monitoring would greatly benefit animal welfare, which would have positive impacts on biodiversity and food safety (Llonch et al. 2017). Policy safeguards should be in place in order to ensure that productivity improvements do not result in land intensification and higher livestock numbers (FAO 2013a).

A great share of livestock production systems in the global North are large and highly industrialised, and already conduct best management practices that make it difficult to further improve herd productivity (Climate Focus; CEA 2014). Countries with intensive livestock systems can primarily reduce their GHG emissions by reducing the extent of methane produced by ruminants via diet additives or supplements (ibid).

In the global South, large livestock herds are managed at lower productivity levels in extensive pasture-based systems (Roe et al. 2019). Herds are likely to have suboptimal diets and nutrition, and take longer to reach slaughter weight, thus their emissions intensity per unit of product is higher (Climate Focus; CEA 2014). In Latin America, large grazing herds are associated with extensive land use change and deforestation (ibid). There is a large potential to improve productivity and reduce GHG emissions in such systems. Over half of developing countries identify the potential to reduce their livestock GHG emissions in UNFCCC communications (OECD 2019a).

Global hotspots for methane emissions from enteric fermentation and manure include South Asia and Latin America, while China and Brazil are the highest-emitting countries (Climate Focus; CEA 2014).

UNEP and CCAC 2021

**Barriers for the implementation of mitigation options**

In extensive pasture systems, there are **practical barriers** to applying required doses and ensuring uptake of feed additives to cattle since they move around freely (Arango et al. 2020).

Many livestock producers in Latin America prefer **traditional production systems** for both simplicity and risk aversion purposes (ibid). Simultaneously, reducing herd sizes by increasing productivity conflicts with smallholder's interest in large herds for non-production functions and risk mitigation (FAO 2013b).

Negative incentives, such as carbon taxes on livestock emissions, can shift emissions from domestic livestock production to imported products from another region. If **sectoral policies for livestock emissions reduction are limited to developed countries**, two-thirds of the emissions reductions would be offset by increased methane emissions in developing countries (Key and Tallard 2012).

There is significant resistance to reducing livestock numbers and related GHG emissions based on **economic interests**. Livestock contributes up to 40-50% of global agricultural GDP (Herrero et al. 2016) and supports the livelihoods and food security of almost 1.3 billion people, around 800 million of whom are resource-poor farmers usually in low- and middle-income countries (GASL 2019). In contrast, global meat and dairy conglomerates are some of the largest emitters, and either underreport or do not disclose their GHG emissions. However, the companies are committed to growth and have power to influence government decisions on detrimental trade barriers or regulations (GRAIN; IATP 2018). Smallholder herds, particularly in the global South, have a role beyond meat and dairy production. Livestock are kept as a form of financial asset, insurance mechanism, or used for labour. Due to their long lives and poor nutrition, their output has very high emissions intensity (ibid). Thus, reducing emissions in smallholder herds has socio-economic implications that must be considered. Livestock rearing plays crucial **social and cultural roles** in certain regions, especially with smallholder herds, and has shaped landscapes across the world (Thornton 2010). Livestock can provide a pathway out of poverty for households, and its social role must be considered when implementing solutions, especially as a form of development aid (Thornton et al. 2007; Moran and Wall 2011). The **socio-cultural role of eating meat** poses an important barrier as a demand-side driver (see also section 2.2). Meat consumption is linked to status, social pressures and norms, and pleasure, and it plays a role in traditions across the world (Macdiarmid et al. 2016).

Livestock production systems contribute to climate change, while climate change impacts will in turn significantly affect livestock production (Rojas-Downing et al. 2017). For example, heat stress may affect the reproductive efficiency, health, and mortality of livestock, and decrease overall productivity (ibid). Increased temperatures can affect feed crop yields and the quality of forage, which can increase methane emissions from ruminants without a shift in diet (ibid).

Incorporating more industrialised measures on pasture-based systems to increase productivity can lead to a multitude of **environmental impacts**, such as increased water pollution and natural resource consumption (Bailey et al. 2014). These measures also raise concerns for animal welfare and zoonotic disease transmission (ibid).

#### Recommendations for overcoming barriers

<u>Policies and regulations</u>

Improvements in production efficiency or increased profits via mitigation options can incentivise farmers to expand their herd size and clear additional land (FAO 2013a). Policies that regulate sectoral emissions and increase land use clearing stringency can prevent unchecked production expansion, provided they do not shift the burden to another country’s export market (ibid).

<u>Awareness raising and capacity building</u>

Policies and programmes that facilitate knowledge transfer are crucial in helping farmers adopt best livestock management practices. Valuable information about mitigation options is being generated by the scientific community, but it is not guaranteed that it reaches farmers in an accessible manner (Arango et al. 2020). Assistance for new technology implementation often ends at the sale point, and does not cover establishment support, which can lead to improper application and negative experiences (ibid).

<u>Financial support</u>

Financial instruments, such as microfinance schemes or subsidies, that support the adoption of new technologies and practices can ease upfront costs for farmers (FAO 2013a). Emissions abatement subsidies or carbon taxes can also incentivise producers to reduce GHG emissions from livestock production, as long as they do not increase overall production output or shift emissions to other countries (Thornton et al. 2007).

### 2.1.5 Carbon storage in agricultural systems

Terrestrial soils are estimated to store twice as much carbon as currently contained in the atmosphere (Ciais et al. 2013). Agricultural practices are a dominant driver of global land degradation which increases the emissions of greenhouse gases and reduces the rate of carbon uptake of soils. Soils under conventional agriculture continue to be a source of GHGs; with total emissions from soils making up more than a third of agricultural emissions (IPCC 2019b, p. 53; Tubiello et al. 2015). This is due to simplified crop rotations, removals of crop residues, separation of arable and livestock farming and losses from soil erosion (Oeko-Institut; Ecologic Institut 2022).

#### Mitigation approaches

To prevent carbon loss from soils, avoiding conversion and degradation of sound ecosystems is of highest priority. At COP21, the initiative '4 permille Soils for Food Security and Climate' was launched, aiming to increase global soil organic matter stocks by 4 per 1000 per year.[13]

- Measures to increase the soil organic carbon stocks of land that is already used for agricultural purposes include e.g. the use of mineral and organic inputs, more residue retention, agroforestry, reducing tillage14 and optimising crop rotation. Growing perennial or cover crops are another way of increasing carbon stored in soils. To improve crop rotations, crops from different categories alternate with each other (primary and secondary cereals, grain legumes, temporary fodders, and to a lesser extent oilseeds, vegetables and root crops). Depleting crops (e.g. maize) are combined with replenishing crops in such systems. Integrating grain and fodder legumes as well as temporary grasslands are particularly beneficial for subsequent crops (Garrett et al. 2017; Peltonen-Sainio and Jauhiainen 2019). Cover crops can reduce nutrient losses, including nitrate that would otherwise be converted to $N_2O$, particularly in riparian areas and waterways (Paustian et al. 2016). That way, the need for external inputs such as fertiliser, feed and energy sources is reduced. In nutrient-deficient systems, additional external fertiliser can be used to increase carbon stored in soils. In grasslands, optimal density of stocking and grazing can increase soil carbon sequestration (Paustian et al. 2016).[15]
- Furthermore, the addition of exogenous carbon inputs such as composts or biochar is discussed as a measure to increase soil carbon stocks. The mitigation effect of exogenous carbon inputs needs to be assessed in the context of a broader life-cycle assessment though. It will depend on where and how the offsite biomass is removed, how it is transported and processed, what their alternative end use would be (burning, adding to landfill or left in place as residues), how it interacts with other soil GHG-producing processes and the condition of the soil to which the inputs are added (Paustian et al. 2016; Minasny et al. 2017).
- Increasing the carbon stored in soils implies multiple other environmental and social benefits. It improves soil health and soil fertility, and thus contributes to food security,

[13] See https://www.4p1000.org/.

[14] SOC stocks under reduced tillage have been found to increase for topsoil or plough layers, while SOC at depths >40cm has not shown to increase significantly as a result of reduced tillage (Minasny et al. 2017).

[15] Additional measures to increase carbon sequestration in agricultural systems include the establishment of hedgerows and flower strips that imply other environmental benefits for habitats and biodiversity as well (Oberč and Arroyo Schnell (2020).

reaching sustainable development goals as well as enhancing biodiversity. It can also improve water quality, make soils more resilient to climate change impacts and counteract land degradation and thus contribute to adaptation objectives. On the other hand, it can also involve negative environmental effects, such as increased $NO_2$ emissions and increase pressure on land tenure (UNFCCC 2019; Paustian et al. 2016; Fujisaki et al. 2018; Bispo et al. 2017).

There is a large variation and uncertainty associated with the carbon sequestration potential of measures to increase the carbon stored in organic soils. Their effect is determined by biophysical factors as well as land-use practices which vary tremendously between different contexts (UNFCCC 2019). The understanding of soil sequestration processes and management options is still limited and implies various knowledge gaps with regard to e.g. temperature sensitivities, interactions among organic matter chemistry, mineral surface interactions and carbon saturation (Paustian et al. 2016). Additionally, the measurement and monitoring of soil organic carbon to produce reliable estimates at country level is difficult and linked to large uncertainties.

#### Mitigation potential

As a result of these uncertainties and due to the fact that studies include a variety of different measures to increase organic carbon in cropland soils, estimates for the technical global mitigation potential of these measures vary significantly and range between 0.2 and 11 Gt $CO_2e$/year [16] (OECD 2019a; Paustian et al. 2016; Zomer et al. 2017; Lal et al. 2018; Minasny et al. 2017). The IPCC Special Report on Climate Change and Land Use (Shukla et al. 2019, chapter 2.6.1) summarised the range of global potentials for $CO_2$ removals by soil carbon management in croplands at 0.25-6.8 Gt $CO_2e$/year in the period 2020-2050. Minasny et al. (2017) conclude that under best management practices, the 4 per mille target can be accomplished.

#### Barriers for the implementation of mitigation options

However, there are various constraints to the implementation of these potentials. On the one hand, **biophysical barriers** (soil structure, nutrients, type of vegetation, water availability etc.) limit the potential of soil organic carbon storage (Fujisaki et al. 2018; Paustian et al. 2016). In dry areas, the potential to grow cover crops or reduce or vegetate fallow fields may be limited (Zomer et al. 2017).

**Lack of the necessary equipment** to implement new management practices poses additional economic barriers at farm level (Paustian et al. 2016). The transaction costs to adapt new cultivation practices might be high and financial benefits might not be available in the short term (Mills et al. 2020). This is aggravated if **existing subsidies or support schemes** do not set incentives for more sustainable agricultural practices (Mills et al. 2020). **Personal attitudes and cultural traditions** (Townsend et al. 2016) as well as a **lack of knowledge** (Ingram 2010) pose additional socio-cultural barriers to changing cultivation practices. The **availability or access to fertiliser** may be another barrier towards increasing carbon stored in soils. Also, shifting cultivation to perennial or cover crops implies lower food yields and economic losses due to lower crop production (Paustian et al. 2016).

[16] However, some of these estimates include biochar as a measure to increase soil carbon stocks. Yet, biochar is not considered as an approach to sustainable agriculture in this paper. Firstly, estimates of high sequestration potentials of biochar rely on unrealistic assumptions regarding the availability of excess feedstock biomass ((Fuss et al. 2018)). To determine the overall mitigation effect of biochar as an exogenous carbon input, a broader life cycle assessment would be necessary ((Paustian et al. 2016; Minasny et al. 2017)). Additionally, the precise interaction of biochar with soils is uncertain ((Smith 2016; Tammeorg et al. 2016)) and experience with large-scale production and use of biochar is still missing ((Fuss et al. 2018)).

Moreover, the carbon content stored in soils is highly variable and sequestered carbon can be lost relatively rapidly. **Approaches and technologies for monitoring carbon stocks** are complex, expensive and very heterogenous across different places (Paustian et al. 2016). Countries in the global South often use a tier 1 method and global default data for measuring soil carbon stocks which provides a weak basis for decision-making on national soil management. Established trade structures, wrong economic incentives and policies supporting industrialised agriculture and large-scale monoculture as well as subsidies for chemical inputs and herbicides pose additional **economic and policy barriers** (UNFCCC 2019). At an institutional/legal level, renting rather than owning land provides disincentives for long-term sustainable soil management (Congressional Research Service 2020). Additionally, changes to soil carbon changes are not necessarily visible in GHG inventories prepared under the UNFCCC. A model covering all types of emission sources from soils does not exist and generally, such models cannot be used on a global scale for all crops and management options (Bispo et al. 2017). This might reduce the incentives for countries to engage in soil carbon sequestration measures in order to pursue mitigation objectives.

Furthermore, **food security** and the expansion of agricultural lands for economic reasons can pose barriers to the conservation of carbon-rich soils that are not used for agricultural purposes yet. Also the conversion of croplands to forest or grassland which implies high potentials for carbon storage will reduce food production and thus not be an option for regions with under-nutrition (Minasny et al. 2017).

**Recommendations for overcoming barriers**

Capacity building and research and development

To overcome technological barriers for improving MRV of soil organic carbon stocks as well as soil management, capacity building would be needed. Also, further research is necessary in order to reduce and manage uncertainties related to soil-based GHG mitigation. To measure the impact on soil health, biodiversity indicators could be used to track the effect of measures tackling soils. Global efforts on monitoring soil carbon would be beneficial and could build on work done by the GlobalSoilMap project[17]. Progress on digital mapping and technology as well as on advancing sampling designs has been made over recent years.

Training and financial support can provide incentives to farmers to change agricultural practices, while participatory approaches appreciating local knowledge can be beneficial.

Policies and regulations

At the level of policies, instruments to promote sustainable agriculture include taxation of nitrogen fertilisers and subsidies for practices that reduce emissions[18] (Paustian et al. 2016; Minasny et al. 2017). To generate further economic incentives, it has been proposed to include soil sequestration projects in carbon crediting markets (Minasny et al. 2017). However, risks related to e.g. permanence and double counting can undermine the environmental integrity of such approaches (UBA 2022).

By emphasising the adaptation and other environmental benefits of measures to enhance soil carbon, mitigation results could be realised as co-benefits. Additionally, measures to secure farmers' and local communities' land rights are necessary (UNFCCC 2019). For different biophysical conditions, tailored and targeted measures need to be identified. ‚No regret' options

[17] See https://www.isric.org/projects/globalsoilmapnet.

[18] E.g. the US Department of Agriculture programmes include mitigation as a conservation goal; provisions in the EU Common Agricultural Policy link subsidy payments to 'cross-compliance' measures that include maintaining the soil organic carbon content (Louwagie et al. 2011).

for improving soil carbon, soil health and soil fertility include using cover crops, agroforestry, restoring degraded land and not burning crop residues (see also sections 2.1.1 and 2.1.7 ) (UNFCCC 2019).

### 2.1.6 Reduction of greenhouse gas emissions from rice cultivation

Rice (*Oryza sativa*) is one of the top three crops grown in the world (IPCC 2019c). Between 1961 and 2019, the cultivated area of rice increased by around 40.5%, from 115.4 million ha in 1961 to 162.1 ha in 2019, contributing to an increase in methane ($CH_4$) emissions (FAO 2021a). Global anthropogenic $CH_4$ emissions from rice cultivation between 2008 and 2017 were 25-37 Mt/year (0.7 – 1.03 Gt $CO_2$e) (IPCC 2021) and estimates for 2019 place global $CH_4$ emissions from paddy rice at 24.08 Mt (0.67 Gt $CO_2$e) (FAO 2021a). $CH_4$ emissions from rice cultivation made up 9% of agricultural farm gate emissions in 2019 (FAO 2021b).

Given $CH_4$'s short atmospheric lifetime and high global warming potential, reducing $CH_4$ emissions from rice cultivation is an effective mitigation option, especially within the next decades (Saunois et al. 2020). Reducing $CH_4$ emissions also reduces direct and indirect negative effects on human health and agricultural productivity (UNEP and CCAC 2021; IPCC 2006). $CH_4$ is a precursor to tropospheric ozone ($O_3$), which is a greenhouse gas that impairs plant physiology and crop health (UNEP and CCAC 2021; IPCC 2006). It has been estimated that a reduction of one million tonnes of $CH_4$ emissions would avoid yield losses from ozone exposure to a degree equating around 31 000 tonnes of additional rice yield (UNEP and CCAC 2021).

#### Mitigation approaches

$CH_4$ emissions from rice cultivation are a result of the anaerobic decomposition of organic material in flooded rice fields (IPCC 1996). The amount of $CH_4$ released from rice fields varies depending on the water regime, the application of organic matter and mineral fertiliser, as well as on soil properties, temperature and the rice variety (IPCC 1996; Tirol-Padre et al. 2018; IPCC 2006). Consequently, changes in agricultural management practices can lead to reduced $CH_4$ emissions from rice cultivation. The overall climate benefit, however, also depends on how $N_2O$ emissions are affected by these management changes, as often there are trade-offs between the mitigation of $CH_4$ emissions and $N_2O$ emissions (Yagi 2018; Kritee et al. 2018).

The water regime of rice is characterised by the rice ecosystem, e.g. whether rice is grown in deep water (>50 cm), is rainfed or irrigated, and by the flooding pattern, which can be continuous or intermittent (IPCC 2006).

- The **water regime of rice**, especially the flooding pattern is a key lever to influence $CH_4$ emissions from rice fields (IPCC 2006), since continuously flooded rice fields generate more emissions than those exposed to aeration (IRRI 2007). **Aeration** can be achieved through periodic drainage of the rice field, which can be carried out in the middle of the growing season, a practice known as **mid-season drainage**, or several times during the growing season, also known as **alternate wetting and drying** (AWD). Another alternative water regime is to replace flooding with controlled or intermittent irrigation, which can lead to increased $N_2O$ emissions, but still has a positive overall effect on GHG emissions (Hussain et al. 2014). **Alternative water management** techniques do not only contribute to reducing $CH_4$ emissions but also reduce water consumption. If done correctly, AWD does not carry significant yield losses (Carrijo et al. 2017). However, changes in flooding patterns to mitigate $CH_4$ emissions can lead to increased $N_2O$ emissions (Wassmann et al. 2009) and in some cases even offset the effects of reduced $CH_4$ (Tirol-Padre et al. 2018).

Additional options to reduce $CH_4$ emissions from rice cultivation include:

- **Improved rice straw management**: When left on the field after harvest, rice straw is commonly either burned or incorporated back into the soil to decompose (IRRI 2007). Although it can have a positive effect on soil quality and nutrient availability, incorporation of rice straw results in higher $CH_4$ emissions in the following growing season, due to the increased availability of organic matter (Yan et al. 2005). In contrast, the practice of field burning of rice straw depletes the soil, emits $CH_4$ and $N_2O$ and negatively affects air quality (Nguyen et al. 2016). If rice straw is instead collected and removed from the field, it can be put to alternative use, for example as substrate for growing mushrooms, as livestock fodder, for composting or for bioenergy production (Gummert et al. 2020). Use of straw for biochar production and application to rice fields can help reduce $N_2O$ emissions and improve soil carbon content (Hussain et al. 2014), but increases in $N_2O$ emissions have also been observed (Olsson et al. 2019).

- **Improved fertiliser management**: Nitrogen concentrations in soil that exceed plant requirements contribute to $N_2O$ emissions (Smith et al. 2007b). These emissions are also influenced by the water regime, the fertiliser type, temperature and soil properties such as pH (Akiyama et al. 2005). The chemical processes leading to $N_2O$ emissions, nitrification and denitrification, are fostered when soils shift condition from wet to dry or from dry to wet (Wassmann and Pathak 2007). Thus, reducing N excess through improved and site-specific fertiliser management is especially important (Sapkota et al. 2021), as this will also influence the overall climate benefit from alternative water management. Regarding $CH_4$ emissions, it has been observed that the use of sulphate-containing fertilisers can reduce $CH_4$ emissions from rice fields (Corton et al. 2000).

- **Changes in planting method**: The two basic rice planting methods are transplanting and direct seeding. For transplanting, rice seedlings are first grown for up to 20 days in a nursery and then transferred to the puddled[19] field. There are also two types of direct seeding, dry direct seeding, where seeds are sown onto dry soil and wet direct seeding, where the soil is puddled and seeds are pre-germinated (IRRI n.d.). The effects of direct seeding are influenced by tillage practices and water management. Direct seeding in combination with irrigation reduces $CH_4$ emissions but increases $N_2O$ emissions (Liu et al. 2014). Still, the GHG intensity of a system with direct seeding and irrigation is lower than under transplanting and AWD (Liu et al. 2014). In combination with no-tillage, direct seeding can lead to higher carbon sequestration in the soil (Chakraborty et al. 2017). But it can also have a negative effect on yield due to declining soil quality or increased competition by weeds (Farooq et al. 2011).

- **Improving rice varieties**: This approach entails breeding rice varieties with plant properties that reduce the release of methane into the atmosphere and/or increase yields. “Low-methane” rice varieties reduce methanogenesis by, for example, allocating less biomass to the roots (Su et al. 2015). Higher yield varieties in turn are expected to help reduce the emissions intensity of rice cultivation considering future growth in demand. Another approach is the development of perennial rice varieties, which if used in “perennial agroecosystems” can support the accumulation of soil organic carbon (Olsson et al. 2019; Huang et al. 2018).

#### Mitigation potential

Emissions from rice cultivation have been steadily increasing in the past, in Asia for example by 0.9% per year (Jia et al. 2019). According to FAOSTAT calculations (FAO 2020a) for 2019, the

[19] A puddled field is wet and has been tilled.

top ten emitting countries of $CH_4$ from rice cultivation were China (5.2 Mt)[20], India (4.6 Mt), Indonesia (2.3 Mt), Philippines (1.6 Mt), Thailand (1.6 Mt), Vietnam (1.3 Mt), Bangladesh (1.1 Mt), Myanmar (1.08 Mt) and Nigeria (0.6 Mt). Other African countries with relatively high $CH_4$ emissions from rice cultivation are Egypt (0.2 Mt), Guinea (0.2 Mt) and Tanzania (0.2 Mt). In Latin America, Brazil (0.1 Mt), Colombia (0.1 Mt) and Peru (0.01 Mt) are the top emitters. However, there remain large uncertainties in inventories of $CH_4$ from rice cultivation (UNEP and CCAC 2021). The top ten rice producing countries in 2020 were China, India, Bangladesh, Thailand, Myanmar, Cambodia, Pakistan, Brazil, the US and Nigeria (FAO 2022).

Estimates of the mitigation potential associated with rice cultivation focus on improved water and rice straw management (cf. Griscom et al. 2017, Höglund-Isaksson et al. 2020, Beach et al. 2015). Already in 2009, it was estimated that midseason drainage and intermittent irrigation can reduce methane emissions by over 40% (Wassmann et al. 2009). Global mitigation potential estimates for improved rice cultivation between 2020 and 2050 range from 0.08 to 0.87 Gt $CO_2e$/year (Jia et al. 2019). These estimates based on other studies vary with regard to whether the technical or economic mitigation potential is considered and whether further resource constraints (e.g. limits to yields) or social or political constraints (e.g. behavioural change, enabling conditions) are considered (Jia et al. 2019). The average emissions intensity of one kg of rice is estimated at 0.9 kg $CO_2e$ (FAO 2021b).

A high mitigation potential is associated with the application of AWD. For example, a 26% reduction in $CH_4$ emissions was observed in Vietnam (Tran et al. 2018) and 35-38% in Indonesia (Setyanto et al. 2018). However, about 35% of the global rice cultivation area are not suitable for AWD, since they lack a reliable water supply (e.g rainfed rice) or drainage capacity (deepwater rice) (IRRI 2014).

Assessments of the mitigation potential of rice must consider how changes in cultivation practices affect $CH_4$, $N_2O$ and $CO_2$ emissions. As mentioned above, changes in water management may reduce $CH_4$ emissions, but can also lead to increased $N_2O$ emissions. Also changes in organic inputs have differentiated effects. Cao et al. (2021) showed that straw incorporation could decrease $N_2O$ emissions, while also lowering $CO_2$ removals by soil and increasing $CH_4$ emissions, with an overall positive effect on GWP.

**Barriers for the implementation of mitigation options**

Rice is a staple food crop in Asia, Africa and Latin America and will be an **important crop to fulfil increasing food demand** from developing countries (OECD and FAO 2020). Estimated global milled rice production in 2020 was 504 Mt (FAO 2022). Rice consumption is expected to increase by 69 Mt by 2029 (ibid). Globally, rice production is projected to increase to 567 Mt by 2030. Production increases by 2030 are mainly expected to come from India, China, Vietnam and Thailand, but significant increases are also expected for the least developed countries (LDCs) in Asia (OECD and FAO 2021). Balancing the need to satisfy an increasing demand and to address associated increases in GHG emissions will pose a challenge for policymakers and farmers.

Rice production takes place over a wide geographic range, at least 113 countries produced rice in 2020 (FAO 2022). This leads to a **wide variety of rice cultivation systems**, which are shaped by environmental and socio-economic conditions (Rao et al. 2017). **Small family farms** (0.5 to 3 ha) predominate rice production in Asia and sub-Saharan Africa (Rao et al. 2017). Consequently, the implementation of mitigation options in rice cultivation faces diverse technical, economic and environmental barriers. Given the predominantly small size of farms in the countries that

[20] According to China's second Biennial Update Report to the UNFCCC, $CH_4$ emissions from rice cultivation in 2014 were at 8.9 Mt, see https://unfccc.int/documents/197666.

will see an increase in rice production, changes in cultivation practices need to be implemented by a large number of farmers, facing different environmental conditions. This poses economic and technical barriers, as farmers often **lack access to the necessary financial means and specific knowledge** to adopt the best management practices. Also, research on the specific mechanisms shaping $CH_4$ and $N_2O$ emissions on the field is still ongoing (see for example Gupta et al. 2021) and knowledge needs to be transmitted to farming practices. At the same time, governments often lack the resources to provide the right support and incentives to farmers.

**Recommendations for overcoming barriers**

Research and development

Rice cultivation practices and environmental conditions are highly variable, even within countries (IPCC 2006), thus $CH_4$ mitigation measures need to be site-specific and targeted. This requires research and the further development of targeted support tools for farmers, e.g. for making on-field decisions. Given the importance of rice as a staple crop in the world and considering that higher $CO_2$ concentrations lead to decreased protein and nutrient levels in rice (IPCC 2019c), further research is required to identify mitigation options for rice that do not have a negative impact on yields and are adapted to drought or higher temperatures. This will also allow to strengthen synergies with goals of food security and resilience.

Financial support

Support to small-scale producers and the provision of incentives are also necessary to elicit change. This will be especially important for LDC countries, where rice production is expected to increase until 2030.

Awareness raising and capacity building

A narrow focus on $CH_4$ reduction in rice cultivation may not lead to net climate benefits, because effects on $N_2O$ emissions and soil organic carbon are neglected (Kritee et al. 2018). Instead integrated changes in management practices, that consider “water, nitrogen and carbon” and are suited to environmental conditions are needed (Kritee et al. 2018; IPCC 2019d).

Policies and regulations

The increase in global demand for rice may pose an incentive for expanding cultivation area. Attention should be paid to prevent this takes place in carbon-rich ecosystems, especially mangroves (IPCC 2019d). Also, a focus on low emissions cultivation practices should be promoted where the expansion of rice cultivation is unavoidable. A focus on demonstrating the benefits for farmers arising from these techniques, such as water saving and potential savings from fertiliser inputs, can support their uptake.

### 2.1.7 Burning practices

Crop residue burning is the practice of burning post-harvest crop stubble from grains to minimise time between harvesting and sowing new seeds. Stubble burning represents an economic and straightforward residue management practice. However, it increases black carbon pollution (with adverse health effects) and GHG emissions, harms soil fertility, and carries the risk of uncontrolled fires. Key drivers of continued crop residue burning practices include the increased amount of crop residuals, labour scarcity, short inter-cropping periods, economic constraints, social influences, and a lack of awareness of adverse impacts.

Most crop residues are left on the field or used for fodder or fuel, since governments have made an effort to ban or regulate crop residue burning. However, burning practices continue to be common in parts of India, China, and Southeast Asia since rapid intensification has imposed economic and practical limitations to good residue management.

25-35% of crop residues originate from rice produced in the tropics, of which 25-40% is burned (Bhattacharyya and Barman 2018). However, these residues can be effectively utilised as mulch, compost, biochar, or used for bioenergy production with notable benefits (Bhuvaneshwari et al. 2019).

Bans on burning practices have been shown to be ineffective without providing alternative methods and technological support. Factors that obstruct alternative uses of residues are a **lack of awareness** of farmers, no secured market for alternative products, or the lack of technology or capacity of small-scale farmers to handle their own waste (Bhuvaneshwari et al. 2019). Establishing government-run crop residue management services or empowering stakeholders via educational campaigns and practical support for use of the residues as a resource can help to change burning practices (Bhuvaneshwari et al. 2019; Hou et al. 2019; Venkatramanan et al. 2021).

## 2.2 Demand-side measures

To reduce emissions from agriculture, and besides changing agricultural practices at the supply side, food-related emissions need to be addressed at the demand side as well. Major changes to food production and consumption are necessary in order to make the agricultural sector compatible with the goals of the Paris Agreement (Clark et al. 2020). 5-10% of total global GHG emissions arise from the supply chain related to the global food system outside the farm gate (IPCC 2019a). Demand side measures to change production and consumption patterns can not only reduce emissions, but also reduce stress on land use and allow for restoration of natural ecosystems and forest due to less land needed for agricultural use (UBA 2020). Three key approaches for reducing emissions from agriculture at the demand side, as well as barriers obstructing their implementation, are outlined below: reducing food waste and losses (section 2.2.1), changing dietary habits (section 2.2.2), and reducing deforestation to create arable land and grassland (section 2.2.3).

### 2.2.1 Reducing food waste and food losses

FAO (2019a) defines food loss and waste "as the decrease in quantity or quality of food along the food supply chain". Waste along the supply chain, not including the retail level, is defined as food loss, whereas food waste occurs at the retail level and the consumption level. In 2019, around 931 million tonnes of food were thrown away globally. Estimates for the share of total food produced that is lost or wasted range from 25 to 30% (IPCC 2019a). The loss of edible food as well as food waste by retailers and consumers entail higher levels of agricultural production, which in turn increases GHG emissions and overall pressure on natural resources (Hiç et al. 2016). During the period 2010-2016, global food loss and waste were responsible for 8-10% of total anthropogenic GHG emissions and created costs of about 1 trillion $USD_{2012}$ per year (IPCC 2019b, p. 58). Additionally, food lost or wasted at farm level is associated with an acidification potential of 12 Mt $SO_2e$ and a eutrophication potential of 10 Mt $PO_{43}e$, water wastage, biodiversity loss (particularly due to waste in meat and animal systems) and land use of about 4.4 million $km^2$ (an area larger than the Indian subcontinent) (WWF 2021).

The reasons for food loss and waste differ substantially in developed and developing countries, and across regions as well as commodity groups. They relate to all stages of the food chain and include pests, natural disasters, weather events, poor agricultural practices, inadequate storage facilities, poor handling practices during processing and transport, market conditions, package design by companies, handling of expiry dates, consumer preferences, and individual behaviour (FAO 2019a; HLPE 2014; WWF 2021; Poore and Nemecek 2018; IPCC 2019b). In high- and middle-income countries, total waste levels at farm stage per capita are higher than in low-income countries (about 700 kg per capita compared to just 500 kg per capita) (WWF 2021).

On the consumer side, food waste is not a conscious decision most of the time. Rather, in developed countries it is a result of not being directly affected by its consequences and by having a distant relationship to the food production process and the efforts related to it (Quested et al. 2013). In contrast to perceptions in the past that food waste is a rich-country problem, FAO and UNEPs Food waste index (2021) finds that the level of household food waste is similar for high-income, upper middle-income and lower middle-income countries.[21]

#### Mitigation approaches

To tackle food waste in different global regions, different approaches are necessary depending on the supply chains and social behaviour of the respective region.

- **Technical options** for reduction of food loss and waste include improved harvesting techniques, improved on-farm storage at farm level and improved food transport and distribution, better infrastructure for storing food, shortening supply chains (new ways of selling, e.g. direct sales) or strengthening food producers' position in the supply chain, and improving packaging during the supply chain (IPCC 2019b, pp. 58–60; HLPE 2014). To implement these options, agronomic training and education for farmers are needed as well as financial support to access technologies and knowledge for better harvesting techniques and improved storage (WWF 2021).
- **Behavioural changes** are needed to reduce food waste, such as acceptance of less-than-perfect fruits and vegetables, higher sensitivity for food waste impacts on a global scale, and improved management of buying and using food at home (Rosenzweig et al. 2020). This implies better planning of purchases, better understanding of expiry dates of food, better storage practices at home, better food preparation techniques, better evaluation of the portions that need to be prepared, making full use of foodstuffs and better knowledge on how to use (Quested et al. 2013). Enhancing the transparency of food chains and communicating external costs could support a change in the behaviour of consumers and producers, but also in the political framework.

Improved food security and nutrition as well as environmental sustainability should be the underlying fundamental objectives of policies and measures for reducing food loss and waste. To support such policies, Poore and Nemecek (2018) suggest that producers should monitor their own impacts, including food loss and waste, and communicate them to processors, retailers and consumers in order to influence their behaviour.

#### Mitigation potential

According to estimates by UNEP (2017), a 45-75% reduction of food waste implies a mitigation potential of 0.79-2 Gt $CO_2$e/year. Reducing post-harvest losses has the potential to free about 2 $Mkm^2$ of land, and another 1.4 $Mkm^2$ could be made available for other sustainable land management options through reduced food waste (IPCC 2019b, p. 62). Reducing food loss and waste also contributes to avoiding deforestation for additional farmland, thereby preserving existing ecosystems and preventing additional emissions (see section 2.2.3).

[21] For low-income countries, a comparison is not possible due to insufficient data.

#### Barriers for the implementation of mitigation options

The **lack of solid data** about food loss and waste presents a major barrier for successful policymaking (FAO 2019a). Also, due to the lack of standards for data collection and commonly agreed evaluation methods, different measurement protocols, different definitions, and different metrics, there is a huge barrier to identify the causes and the extent of food loss and waste (HLPE 2014).

Only when the entailed costs of reducing food loss and waste are outweighed by the benefits, will suppliers and consumers undertake the necessary efforts. A general **lack of access to credit** can be a barrier to implement measures to improve harvesting and handling techniques or choosing most appropriate crops. Without financial help some farmers, especially smallholders, cannot afford the costs for better harvesting and storage technologies (FAO 2019a). Low world market prices and dependency of smallholder farmers on **asymmetric trade structures** that may imply last minute cancellations may mean that farmers cannot afford to harvest surplus food (WWF 2021).

Next to a lack of funds, also a **lack of information, the distance to markets, and weak tenure security** are challenges private actors are faced with (FAO 2019a). In particular, power imbalances between farmers and retailers are structural drivers that keep farmers' incomes supressed and maintain the status quo (WWF 2021). Additionally, a lack of awareness as well as a lack of appropriate storage options obstruct change at behavioural level.

Food consumption varies from country to country as much as meals do, it is challenging to generalise barriers at a global level. It is therefore crucial to consider the local context in order to identify the most important reasons for waste at farm level and link them to underlying drivers operating at national or international level (WWF 2021).

#### Recommendations for overcoming barriers

<u>Policies and regulations</u>

Governments should take action to reduce food loss and waste along the whole food chain. Also, **investments in infrastructures** are necessary in order to implement better storing of food (HLPE 2014). **Food processing needs to be improved and developed** as well to address food loss and waste. Various actors along food chains need access to and knowledge of the necessary technologies to that end. Agricultural policies and subsidies should include incentives to reduce food waste.

Also, **standards to increase animal welfare** to address intensive meat production methods and strengthen the regulation of fishery practices to reduce bycatch can contribute to reducing food waste (WWF 2021). **Waste policies** should be designed in a way to explicitly deal with food by including incentives to avoid food waste generation and by managing food waste separately from other waste (HLPE 2014). To increase the political commitment to reducing food waste, reduction targets from 'farm to fork' should be integrated in national and global food waste initiatives, goals and programmes (WWF 2021).

<u>Financial support and capacity building</u>

Additionally, **agronomic training and education** for farmers as well as other actors along the food chain is necessary to change practices (HLPE 2014). This needs to be combined with financial and technological support, e.g. through microfinance initiatives to farmers in order to take up innovations, adjust crops to minimise food loss and increase access to cooling (WWF 2021). Additionally, farmers need to be paid **fairer prices** in order to be able to improve harvesting and field management techniques. Market regulations and fair trade laws promoting contractual arrangements to share risks more equitably between producers and retailers are further necessary to empower farmers to address food waste at farm level (WWF 2021).

Awareness raising

At **consumer level, advocacy and education** is necessary to promote knowledge on food loss and waste as an incentive to change behaviour. Increasing the variety in our diets can help to reduce incentives for cultivating less suited but very popular plant varieties for specific regions. This needs to be supported by **expanding product specifications** to lower the standards for shape and appearance of food, especially fruits and vegetables, at governmental level (WWF 2021). Additionally, **date labelling policies** need to provide clear signals to consumers and can help to cut food waste at consumer level (HLPE 2014).

Research and development

Furthermore, **technical options could support behavioural changes by consumers**, such as better packaging or the development of “doggy bag” practices in restaurants (HLPE 2014). Food banking by non-governmental initiatives to distribute surplus food can also support efforts to reduce food loss and waste. Governments need to guarantee an institutional environment that favours donations, e.g. by providing the right tax-related incentives and encouraging civil responsibility (HLPE 2014).

**Effective monitoring and evaluation of the measures** taken is necessary. However, the limited data currently available should already be used for informing businesses and consumers about food loss and waste. Even with missing information on where losses occur for example, measures such as improving credit access for farmers and suppliers could be executed. The experiences on best practices for reducing food waste and losses could be exchanged on a regular and international basis among science and politics to reach global improvement and promote public interest and debate on the issue.

### 2.2.2 Changing dietary habits

Eating habits of developed countries and emerging economies still depend on using farmland in poorer countries to produce their preferred food: currently, one third of arable land worldwide is used for producing crops for feeding livestock. The FAO predicts a continuous growth of meat and dairy products worldwide (FAO 2018a). Changing dietary habits offers a lot of potential for tackling the question of food security and reducing GHG emissions (see chapter 2.1.4 on a discussion of emissions caused by livestock). However, promoting changes to dietary habits is politically sensitive as it affects people’s freedom of choice and established habits may be deeply rooted in social and cultural traditions that are difficult to break with.

Sustainably changing dietary habits involves a general of per capita consumption of calories to healthy levels (in regions with overconsumption) as well as adopting a plant-rich diet. Excluding animal products from the diet can make a huge difference, whereas reducing beef consumption plays a pivotal role (Clark et al. 2020; WRI 2016). Poore and Nemecek (2018) find that even the lowest-impact animal product has higher impacts across eutrophication, acidification, land use, and GHG emissions compared to the average impact of substitute vegetable products. According to Pieper et al. (2020) animal-based products cause external costs (2.41 €/kg product), which are 10 times higher than dairy costs and 68.5 times higher than plant-based costs.

At present, unhealthy diets are a leading cause of mortality, with more than 1.9 billion people being overweight (WHO 2021) while about 800 million people faced hunger in 2020 (FAO et al. 2021). Shifting to more sustainable, healthier diets (FAO 2020b) could help to reduce health costs linked to diet-related mortality and diseases *and* climate change costs by 2030, as their hidden costs are lower than those of current food consumption patterns (FAO 2020).

While healthy diets are currently not affordable for more than 3 billion people, the savings implied by a shift to healthier diets could be invested to lower the cost of nutritious food (FAO 2020b). Additionally, more than 40% of global crop calories are used as livestock feed today (Pradhan et al. 2013). With radical changes to current dietary choices, the current production of crops would be sufficient to provide enough food for a projected global population of 9.7 billion in 2050 (Berners-Lee et al. 2018). Shifting diets can therefore be considered as a strong tool to ensure food security for a global population (UBA 2021).

**Mitigation approaches**

The EAT Lancet Commission has proposed scientific targets for healthy diets as well as sustainable food systems. These targets are integrated into a common framework, the safe operating space for a food system with benefits for human health and the environment. Adhering to this framework is estimated to make it possible to provide healthy diets for about 10 billion people by 2050 within a safe operating space. The proposed framework is universal for all food cultures and production systems but the reference diet can be adapted to local cultures and traditions within the defined boundaries of food production (Willett et al. 2019).

Implementing this framework will affect the whole food production system and requires major global efforts. Yield gaps need to be reduced by at least 75%, nitrogen and fertiliser use need to be redistributed globally, recycling of phosphorus needs to increase, the efficiency of fertiliser and water use in agricultural production needs to increase, mitigation options to reduce GHG emissions from agriculture as outlined in chapter 2.1 need to be implemented on a large scale and production priorities need to shift to align with the proposed framework. The proposed strategies to achieve a 'Great Food Transformation' include 1) seeking international and national commitment to shift towards healthy diets; 2) changing agricultural priorities from producing high quantities of food to producing healthy food; 3) sustainably intensify food production to increase high-quality output; 4) strong governance of land and oceans to protect ecosystems and ensure resilience and productivity in food production and 5) reduce food losses and waste by at least 50% (Willett et al. 2019).

Approaches to change dietary habits include

- **Internalising the environmental costs of meat production** to reduce the total amount of animal-based products. This could be achieved by increased taxes on animal-based products to target the demand side as well as to put higher taxes on excess nitrogen (animal manure) to address the supply side.
- **Behavioural changes** by consumers to make their diets more sustainable and healthier (where food security is not an issue). This can be supported by investing in education and public health information. Also, better coordination between health and environment departments is needed at a national or regional level (Willett et al. 2019). Besides substituting animal products through plant proteins, another option would be to promote alternative food production systems, including the use of more insect protein in diets which is practised in many cultures already. Insect-based food is more environmentally friendly than livestock (Carvalho et al. 2020) and has been found to bear large potentials to increase food security (Dickie et al. 2020).

Shifting diets to reduce the overconsumption of calories, proteins and beef specifically is necessary for populations who are currently overconsuming calories or protein or consume very high amounts of beef. The proposals to change dietary habits outlined in this chapter do not target under- or malnourished populations and do not target livestock providing livelihoods to poor smallholder farmers (WRI 2016).

#### Mitigation potential

The estimated technical mitigation potential of dietary changes range from 0.7 to 8.0 Gt $CO_2e$/year by 2050 (range of 'healthy diet' to vegetarian diet). This includes reductions in emissions from livestock and soil carbon sequestration on spared land. Yet, co-benefits with health are not taken into account in this estimate (IPCC 2019b, p. 58; Roe et al. 2019). According to Hawken (2017), 2.2 Gt $CO_2e$ could be mitigated if 50% of the global population adopted diets restricted to 60 g of meat protein per day (including emissions from land use change).

Changing dietary habits (as well as reducing food waste) will increase the potential for other options such as land sparing and sustainable land management options such as restoration of forests, peatland and semi-natural permanent grassland as they have the potential to free 80-240 million ha (IPCC 2019b, p. 62).

#### Barriers for the implementation of mitigation options

A widespread behavioural change will be hard to achieve in a short amount of time. Even with strong data changing everyday consumption habits is a long-term issue that needs multifactorial and continuous influence in media, schools and other parts of society.

For policymakers and business who need and demand guidance, the **absence of clear scientific targets for achieving healthy diets** from a sustainable global food system is a barrier for taking action and pursue coordinated efforts (Willett et al. 2019).

On a personal level, changing diets interacts with peoples' **subjective freedom of choice** as well as with **social and cultural habits** and is therefore politically sensitive. Additionally, the benefits of sustainable diets have so far not been communicated properly and shifts to such diets have appeared disruptive to consumers (WRI 2016). A barrier against the use of insect protein in diets is the low acceptance of insect-based food in Western societies (Wendin and Nyberg 2021). Moreover, regulation is lacking to bring insects into food supply systems in Western countries (Dobermann et al. 2017).

Additionally, the global consolidation of the food industry has created large-scale actors with global influence on dietary habits. As a result, the food industry is driven by **economic interests** that are challenging to address politically (GRAIN; IATP 2018).

#### Recommendations for overcoming barriers

The transformation that is required to change the global food system requires engagement from actors at all levels. To break established habits and promote behavioural shifts, WRI (2016) describes four strategies: 1) minimise disruption with established habits by replicating the experience regarding taste, look, texture; 2) selling a compelling benefit of more sustainable products, e.g. as they meet current key needs or are cheaper than more unsustainable products; 3) maximise awareness and display of sustainable products in a retail environment or cafeterias/restaurants; 4) evolve social and cultural norms through information and education campaigns or making food socially acceptable or unacceptable through media campaigns.

<u>Policies and regulations</u>

While governments need to set goals for an environmentally friendly food system, take respective policy action and set the right market incentives, industry needs to allocate funding to more sustainable products and civil society needs to promote action by campaigns and public education. Procurement policies can help to promote healthy diets in workplaces, schools and other venues where meals are publicly provided (Willett et al. 2019). Additionally, incentives can be provided by public subsidies for healthy and environmentally friendly food and higher taxation of those products that have harmful effects on human health and the environment (Sisnowski et al. 2017). Taxes have been found to have greater impact on consumption if they are applied in broader regions instead of single countries, if the substitutes are taxed as well and if the taxes are sufficiently high (WRI 2016). Better coordination between health, agriculture, water and environment departments is needed to ensure coherence among policies affecting sustainable diets (WRI 2016).

Awareness raising and research and development

Tools like a transparent labelling system for the nutritional value of processed food can help to promote a healthier diet to societies but have been found to have limited effects so far (WRI 2016).

To overcome reservations against alternative protein sources, clear communication that insects are a valuable food resource is necessary (Wendin and Nyberg 2021). Additionally, more research is needed regarding approaches for processing and storing insect-based food and set appropriate regulatory standards (Dobermann et al. 2017).

### 2.2.3 Reducing deforestation to create arable land and grassland

Agricultural expansion continues to be the most widespread form of land use change (IPBES 2019) and consequently, the largest source of AFOLU emissions. Eliminating net deforestation in the next decade is a key component of emissions pathways consistent with limiting global warming to 1.5°C. As part of this, annual deforestation rates should be substantially reduced by 70% (compared to 2018 levels) by 2030 and by 95% by 2050 (WRI 2020).

Agricultural expansion is particularly concerning in the tropics due to the broad expanses of remaining old-growth forest and the high carbon density of that forest. Around 60% of tropical deforestation is driven by expansion of agricultural land for cropland, pastures and plantations, with cattle and oilseed the largest contributors (Pendrill et al. 2019). If demand for these products is reduced, less land is needed to grow animal feed and energy crops which in turn reduces the pressure on ecosystems.

Reducing further agricultural expansion and its associated deforestation provides a slew of environmental and social co-benefits. IPBES (2019) identified land use change as the direct driver with the greatest negative impact on nature since 1970. Eliminating net deforestation allows for the preservation of natural habitats and minimises biodiversity loss. Reducing biodiversity loss is important in and of itself but also for agricultural production, for example in maintaining pollinator diversity.

Forests provide a significant amount of ecosystem services that are otherwise lost to deforestation. For example, wild food foraged in forests provide a safety net for rural families (Brandon 2014). Tropical forests are also closely linked with human health. Deforestation causes changes in disease vectors, as seen in increased malaria incidences where forests have recently been cleared. Many traditional medicines are derived from forests, serving as many as 4 billion people (ibid).

Additionally, forests are crucial for preserving soil quality and preventing topsoil degradation, which is especially relevant in tropical forests that characteristically have a shallow top layer. Surface erosion can increase the chances of landslides and reduce water quality downstream (ibid).

**Specific mitigation measures**

Reducing deforestation emissions from agricultural expansion can be broadly addressed in two ways; (1) measures that directly target deforestation and preserve forested areas, and (2) measures that reduce the demand for new agricultural land and its expansion into forests.

Measures that directly target reductions in deforestation include improved governance for the legal protection of forested areas and reforms to private sector supply chains to reduce illegal deforestation.

- The majority of natural land is owned by governments and is only converted, or deforested, when reclassifications are granted (if not illegally). National governments can refuse to turn over land, but this poses political and financial challenges since land concessions are a substantial source of revenue (WRI 2019). Establishing protected natural areas and recognising lands for Indigenous Peoples can also lead to reduced deforestation levels, especially if the land has high agricultural potential (ibid).

- Agricultural supply chains are long and involve many actors, meaning that consumers are detached from any upstream deforestation occurring. Improving the transparency and sustainability of supply chains can help to reduce illegal deforestation. Achieving this sustainability can be challenging but there are measures that governments and private sector actors can take. Governments can require companies to undertake due diligence in their supply chains, can require financial investors to disclose risks, and provide incentives for the sustainable management of forests. Many companies have signed up to declarations for reducing deforestation in their supply chains, such as the New York Declaration on Forests. More could follow their lead and all need to follow through with implementation.

  One successful example of a value chain intervention is the Brazilian Soy Moratorium (BSM), which helped to decouple soybean expansion from Amazon deforestation, along with the expansion of protected area and crack-downs on illegal deforestation (WWF; BCG 2021). The BSM is an agreement between NGOs and companies to not buy soybeans cultivated on deforested land (PROFOR 2018). This supply-chain governance can be integrated into existing public policies to help smallholders increase their productivity and incomes on existing agricultural land (ibid).

Reducing the demand for new agricultural land means being able to meet much of the increasing food needs on existing agricultural land. Many of the mitigation options addressed in other sections can help to reduce land use pressures by improving productivity, shifting to less land-intensive products (section 2.2.2), or reducing food waste and loss (section 2.2.1).

- Changes to existing farming practices that sustainably intensify production, such as optimised fertiliser use, can reduce the demand for new land while maintaining or expanding productivity (Folberth et al. 2020). Crop production has the potential to double if attainable yields were achieved on present cropland (ibid).

- Land and soil degradation result in decreased crop yields, which drives the need for new land. Restoring degraded farmland can reduce the pressure for agricultural expansion. Employing conservation agriculture practices such as no-till and integrated soil fertility management to replenish lost nutrients can result in higher yields that reduce incentives to expand production (see also sections 2.1.1 and 2.1.5).

**Mitigation potential**

Reducing deforestation and forest degradation have the largest mitigation potential in the AFOLU sector (0.4-8.6 Gt $CO_2$e/year) (IPCC 2019b, p. 49). Not all deforestation and forest degradation is driven by agricultural expansion so this IPCC estimate would represent an upper limit to the mitigation potential from reduced agricultural expansion. An estimated 60% of deforestation in the tropics is driven by agricultural expansion, of which 69% was conducted in violation of national laws and regulations (Forest Trends 2021).

**Barriers to implementation**

Increasing demand for food as a result of population growth and changing consumption patterns make it difficult to advocate for reduced agricultural land expansion. Reducing **agricultural expansion is also at odds with economic interests for expanding agricultural productivity**. Those with investments in the agriculture sector have strong political and economic power.

A **lack of political will** can pose a challenge to regulating deforestation. Governments may do little to restrict deforestation, particularly when it is an economic asset (Kalaba 2016). Domestic policy is also an issue of sovereignty, and international pressure to reduce deforestation may not be welcome. On the other hand, many governments struggle with **weak enforcement capacity**. The enforcement of regulations is handled by understaffed and underfunded environmental authorities. For example, just three agencies are responsible for regulating the 40 million hectares of forest in the Amazon (Furumo and Lambin 2020).

Key challenges with reducing deforestation are that the drivers are indirect (e.g. demand for palm oil products) and that **many actors are involved in long supply chains** that are often international. With many actors involved, it is possible for all to step back from responsibility.

Deforestation is also **difficult to monitor and control**, meaning a lack of transparency. This applies both to what is actually happening on the ground in terms of trees cut down, and also to the multi-actor supply chains involved that may be spread internationally, adding to the challenge of holding someone accountable (NewClimate Institute 2021).

There are limits and possible trade-offs in the intensification of farming to reduce demand. For example, monocultures allow for more intensive farming but may lead to local biodiversity challenges. Other efforts to improve landscape restoration and in turn, improve yields face economic challenges, such as labour force availability and unattractive opportunity costs that impede the adoption of restorative agricultural practices (Pinto et al. 2020).

Finally, all barriers that pertain to the other mitigation options that reduce the drivers for agricultural expansion also indirectly apply to reducing deforestation rates.

**Recommendations to overcome barriers**

Policies and regulations

Agricultural expansion and related deforestation is a complex issue with a variety of underpinning drivers, and there is no one-size-fits-all solution. That is why a context-specific, systems perspective that addresses drivers at all elements of the supply chain is necessary. For instance, on option could be to develop multilateral public-private partnerships to engage diverse stakeholders while synergising public policies with private zero-deforestation and supply chain initiatives (Furumo and Lambin 2020). Downstream actors in agricultural supply chains can be held legally responsible for ensuring that their products are not driving deforestation (European Parliament 2020; Hughes and Terazono 2020).

The policy frameworks addressing deforestation have the potential to be strengthened. In the 25 national governments that manage 87% of the world's remaining tropical forest, sustainable forest use and conservation should be central to national development plans (Global Canopy

Programme 2015). However, this will require resources put into enhanced monitoring and enforcement of regulations. Other governments can facilitate a reduction in deforestation rates by introducing policies that exclude or ban illegally or unsustainably harvested forest commodities or by financing zero-deforestation measures in forest-owning countries (ibid).

Land tenure plays a critical role in agricultural expansion and land degradation. Stakeholders are less willing to invest in sustainable agriculture practices that ensure the longevity of the land and soil when their rights to continued access to the land are not secured (UBA 2021). Deforestation has been driven in part by the "race to the frontier", where forest has been prematurely cleared to establish land rights (Angelsen 2010). Although it is a highly sensitive issue, reforms to improve tenure security will reduce deforestation and agricultural practices that drive land degradation, since farmers will be more willing to invest in the land (ibid).

Financial support

Financial incentives, such as reformed agricultural subsidies and linking domestic credit lines to policies and best practices, can support producers transitioning towards sustainable agricultural production and forest use (ibid). On the contrary, the financial onus of ecologically destructive products can be placed on consumers, which can reduce the demand for land-intensive products such as soy and meat (Boerema et al. 2016).

# 3 Clustering barriers for ambitious mitigation in the agricultural sector

The analysis in Chapter 2 shows that similar reasons for not implementing ambitious mitigation action in the agricultural sector play a role for different mitigation options. Additionally, a myriad of different barriers obstruct changes at different governance levels. (2019b). In this chapter, we cluster identified barriers in the chapters above according to the relevant governance level for taking action, while taking into account the classification from the IPCC Special Report on Climate Change and Land (IPCC 2019b) which differentiates six types of barriers which obstruct mitigation action in the agricultural sector.

It must be noted that the relevance of specific barriers strongly depends on local circumstances. At the most basic level, biophysical conditions define the framework for appropriate mitigation options. These include climate conditions and soil structure, but also farm size and the type of agricultural activities that are prevalent. The assessment, planning and implementation of national climate policies in the agricultural sector as well as approaches for overcoming existing barriers will therefore need to be context-specific (OECD 2017; IPCC 2019a).

**Economic barriers**

Economic barriers imply that, for example, markets and market actors work against more ambitious climate protection in agriculture. These include, for example, the provision of cheap food at world market prices, which makes investments in climate-friendly technologies unprofitable; established infrastructures (e.g. for animal food (stables, dairies, slaughterhouses); lack of sales markets for climate-friendly food, etc.). Regulatory and institutional frameworks can be adapted to overcome these barriers.

**Policy/legal barriers**

These include existing laws and regulations, financial incentives or resources, and the design of support instruments at national, regional, and international levels, some of which are counterproductive to ambitious climate action in agriculture. For example, land tenure rights might obstruct changes to alternative management practices and subsidies for fertiliser might incentivise over-application. Policy barriers may also be created by policies that primarily address issues other than agriculture but can still produce constraints or conflicts for the agriculture sector.

**Technical barriers**

Especially the efficient use of nutrients, but also soil cultivation and animal feeding require detailed knowledge and the availability of appropriate technologies. Great potential lies in the optimisation of agricultural production processes through further education, good management, the use of climate-friendly technologies, and detailed knowledge of local conditions (e.g. soils, climate, animals).

Additionally, the lack of data to estimate emission factors for agricultural mitigation activities as well as limited capacities to establish robust MRV systems provide challenges to design ambitious mitigation policies (WRI; Oxfam 2019; FAO 2018b).

**Socio-cultural barriers**

Behavioural and lifestyle patterns but also values and guiding principles influence our diet (e.g. high consumption of animal food) and the type of agricultural production (e.g. animal husbandry).

**Institutional barriers**

Institutional barriers due to different responsibilities and division of competencies complicate reform processes. For example, the location of agricultural, climate, food and trade policies in different ministries is widespread and can lead to competing policy objectives. Lack of administrative support or political attention, or the nature of agricultural education are also important factors. Examining all policy objectives for compatibility with climate change goals can help governments overcome institutional barriers.

**Biophysical or environmental barriers**

These include factors that reduce fertile land areas for food production, such as salinisation, temperature rise, or extreme weather events like floods or drought. Decreases in productive land areas are accelerated by climate change and increase pressure on existing agricultural land areas. Resilient agriculture is often characterised by high diversification of land use. Agroforestry, in particular, combines resilient food production with carbon sequestration and has been increasingly cited in recent years as part of the solution to the problem.

## 3.1 Farm level

A number of the identified barriers operate at the **farm level**:

- Economic barriers
    - The **lack of specific economic benefits** to farmers act as a barrier to the implementation of mitigation measures at farm level. If change implies **high adoption/transaction costs** at the farm level, particularly with regard to capital costs, this will inhibit farmers from changing their practices (OECD 2017; Smith et al. 2007a; Mills et al. 2020). **Lack of access to credits** for investing in infrastructure, machinery and equipment with high implementation costs reinforces this barrier and plays a particularly important role if climate-friendly practices result in lower yields or profits (OECD 2017; Wageningen University 2014). Lacking financial resources to invest in better harvesting and storage technologies have also been identified as a barrier to reducing food loss and waste at the farm level (FAO 2019a). **Uncertainty about the impact of changing agricultural practices** on farm business is a further barrier to change (Kragt et al. 2017). Additionally, mitigating emissions might conflict with other priorities of farmers; particularly if they operate at subsistence level.
    - Such barriers are reinforced by **structural factors, such as farmers' age or farm size**, that will impact the likelihood of implementing innovations (OECD 2017; Mills et al. 2020; Knowler and Bradshaw 2007).
    - Furthermore, **cooperation with industries** can obstruct changes in crop cultivation, e.g. if contracts have been concluded that focus on yields or if relations with processing factories are long-established (OECD 2017).
- Policy/legal barriers
    - A farmer's decision to adopt climate-friendly measures depends on **property rights and the regulation of land tenure**, with long-term land tenure positively affecting the willingness to apply climate-friendly measures such as sustainable soil management (OECD 2017; Aryal et al. 2020; Congressional Research Service 2020). If there is no clear ownership by a single party defined, this might inhibit the implementation of management changes (Smith et al. 2007a).

- Lack of **institutional support, advice or information** available to the farm level was also found to act as a barrier to the adoption of more sustainable farm management practices (Mills et al. 2020).

► Technical barriers

- Lacking awareness of farmers but also the **lack of technology** or capacity of small-scale farmers can be a barrier to changing agricultural practices, e.g. abandoning unsustainable burning practices of agricultural waste in India, China and Southeast Asia (Bhuvaneshwari et al. 2019), changing crop management, implementing agroforestry practices or reducing GHG emissions from rice cultivation.

- Additionally, **lack of awareness** of climate change and its consequences and a **lack of knowledge** about mitigation measures and their benefits and how to implement them has been found to prevent farmers from investing in GHG mitigation measures in Southeast Asia (Aryal et al. 2020). Studies from India and the US have shown that famers lack awareness of the relationship between fertiliser application and climate change, for example, and receive advice for how to apply fertilisers from economic actors with vested interests (Stuart et al. 2013; Pandey and Diwan 2018).

► Socio-cultural barriers

- Further factors at farm level relate to **personal attitudes, traditions and practices** which will impact the acceptance of mitigation measures (OECD 2017; Mills et al. 2020). Risk aversion has also shown to be a significant social barrier to reducing fertiliser overapplication (Robertson and Vitousek 2009). Additionally, gender roles might act as a social barrier to access to information (Aryal et al. 2020). Particularly in the context of smallholder farming, the social and cultural role of livestock rearing, as well as the dependency of livelihoods on livestock, are strong arguments against reducing the emissions from livestock by reducing the number of animals (Herrero et al. 2016; Thornton 2010).

► Biophysical/environmental barriers

- The **reversibility of emission reductions** or carbon sequestration in the agricultural sector can act as a biophysical barrier to the implementation of mitigation measures, e.g. by inhibiting farmers to implement climate-friendly cultivation practices because the outcomes might not be permanent (Aryal et al. 2020).

## 3.2 National level

At the national scale, different types of barriers can obstruct enhancing mitigation in the agricultural sector:

► Economic barriers

- Firstly, resistance against mitigation options emerges from perceived **potential negative effects on production**, particularly in countries, where agriculture is an important sector for the economy (OECD 2017). If deforestation brings economic advantages, political will may be weak to implement stricter regulation (Kalaba 2016). **Economic objectives to increase agricultural output** might also act as barriers against more sustainable forms of agricultural production (e.g. the Australian government set the goal of increasing farm gate output to AUD 100 billion (from AUD 66 billion) by 2030[22]).

- In regions where **food security** is the predominant policy objective, the intent to increase production levels might even prevent the protection of carbon-rich soils that are not used for agricultural purposes yet (Minasny et al. 2017).

► Policy/legal barriers

- **Policies to support production, such as input subsidies or tax exemptions**, may pose obstacles to climate-friendly agricultural practices (OECD 2017), as they imply that more revenues can be generated with conventional, intensive, monocrop cultivation systems (Oberč and Arroyo Schnell 2020). For example, crop subsidy payments based on the extent of production perversely promote fertiliser overapplication (Robertson and Vitousek 2009). Likewise, existing financial incentives often target anaerobic digester construction rather than the value of the output, which does not stimulate farmers to improve their manure management. Replacing synthetic fertiliser with manure is disincentivised by existing fertiliser subsidies (Tan et al. 2021). The largest share of direct production subsidies provided to farmers at global scale goes to the largest farms that are better equipped to handle price and income fluctuations by themselves than small-scale farmers (Searchinger 2020). Also, most support of current governmental support for agriculture in OECD countries has been found to fund larger and wealthier farms, missing the chance to support smallholder farmers in boosting productivity and securing their livelihood. Only a limited portion of this support is used to drive climate mitigation, albeit environmental conditionality for agricultural support has become more stringent in recent years (World Bank 2020).

► Technical barriers

- **MRV systems** defining the way in which emissions are reported and accounted for may provide barriers at the national level. Many mitigation practices are not captured in the inventory accounting if countries are not applying Tier 3 methodologies of the IPCC inventory guidelines. This reduces the recognition that governments can gain from implementing mitigation policies in the agricultural sector (OECD 2019b). Other environmental benefits are not taken into consideration in this accounting at all. ISO methodologies to quantify GHG emissions and removals for products or organisations do not take into account soil effects.

- Furthermore, data on emissions related to soil carbon stock changes resulting from land cover, land-use change or soil use in production processes is missing. Emissions projections for soils are not covered by available standards and no guideline is yet available for estimating C stocks at regional level (OECD 2017; Bispo et al. 2017).

- Regarding food waste and loss, the lack of solid data presents a major barrier for successful policymaking (FAO 2019a).

► Socio-cultural barriers

[22] See https://www.awe.gov.au/sites/default/files/documents/ag-2030.pdf.

- Additionally, **lack of education and awareness** on the negative effects of agriculture on climate change can act as a barrier against more climate-friendly practices at the level of policymakers (OECD 2017).

► Institutional barriers

- The **absence of a well-designed climate policy** that includes the agricultural sector can act as a barrier to mitigation practices in that no incentives for these practices are available (OECD 2017). This can result from a **lack of a goal or vision of sustainable agriculture** that prevents coherent policy incentives for sustainable practices (Oberč and Arroyo Schnell 2020). It is also challenging to design policies that reach different types of stakeholders, ranging from small-scale farmers to large-scale producers. Moreover, a lack of a clear policy and coordination between different governance levels or ministries hinder the implementation of ambitious mitigation action (Aryal et al. 2020). This can, in turn, send mis-matching incentives to farms on priorities for their management practices. For governments in the global South, weak enforcement capacities and understaffed and underfunded environmental authorities pose barriers to effective regulation of deforestation for agricultural purposes (Furumo and Lambin 2020).

## 3.3 International level

Barriers at the **international level** arise from the following aspects:

► Economic barriers

- Economic competition between countries posing barriers to implementing mitigation policies: the possibility of **carbon leakage** to other countries as a result of stricter mitigation policies in one country which will put this country at disadvantage in the competition with others (OECD 2017). Particularly introducing sectoral policies for livestock emissions reduction only in the global North would imply that two thirds of the emissions reductions would be offset by increased methane emissions in the global South due to shifting from domestic production to imported livestock products (Key and Tallard 2012).

- The global consolidation of the food industry has created large-scale actors with global influence on dietary habits. As a result, the food industry is driven by big **economic interests** that are challenging to address politically (GRAIN; IATP 2018).

- As agricultural trade is globalised, there are **long supply chains** for agricultural products that act as indirect drivers of deforestation (e.g. the demand for palm oil products). With many actors involved, regulation as well as monitoring of deforestation at global level is challenging.

► Policy/legal barriers

- **Insufficient financial support** to the agricultural sector may also pose obstacles to adopting climate-friendly agricultural practices (Aryal et al. 2020).

- Low world market prices and dependency of smallholder farmers on **asymmetric trade structures** are a major barrier to tackling food loss and waste as they may imply last minute cancellations and these may mean that farmers cannot afford to harvest surplus food (WWF 2021). Power imbalances between farmers and retailers are structural drivers that keep farmers' incomes supressed and maintain the status quo (WWF 2021).

- Mitigation measures in the agricultural sector might conflict with **international trade law**, e.g. if support provided to national producers reducing GHG emissions in their production at the same time contributes to promoting increased exports or replacing imports; if climate-'unfriendly' products and production methods are taxed at the border or if labelling to inform consumers is not based on internationally agreed standards (Häberli 2018).[23]
- **Free trade agreements** can induce governments to shift subsidies so that they are less market-distorting but this was not found to have significant effects on global emissions (Searchinger 2020).

► Technical barriers

- The **lack of common metrics and indicators** acts as another barrier to implementing mitigation action in the agricultural sector. If quantitative evidence of the benefits of a measure is not available, it will be difficult to convince famers, consumers or policy makers to support change (IUCN 2020). For example, due to the lack of standards for data collection, no commonly agreed evaluation method, different measurement protocols, different definitions, and different metrics, there is a huge barrier to identify the causes and the extent of food loss and waste (HLPE 2014).
- Also clear scientific targets for achieving healthy diets are missing, thus obstructing a shift to a sustainable global food system (Willett et al. 2019).
- With regard to halting deforestation, challenges to monitoring and controlling, meaning a **lack of transparency** pose a barrier to effective international action. This applies both to what is actually happening on the ground in terms of trees cut down, and also to supply chains with multiple actors involved that may be spread internationally, adding to the challenge of holding someone accountable (NewClimate Institute 2021).

## 3.4 Consumer level

Barriers at the consumer level mainly relate to socio-cultural aspects:

- Food culture and tradition acts as a barrier at consumer level: Changing diets interacts with peoples' **subjective freedom of choice** as well as with **social and cultural habits** and is therefore politically sensitive. Additionally, the benefits of sustainable diets have so far not been communicated properly and shifts to such diets have appeared disruptive to consumers (WRI 2016). A barrier against the use of insect protein in diets is the low acceptance of insect-based food in Western societies (Wendin and Nyberg 2021). Additionally, regulation is lacking to bring insects into food supply systems in Western countries (Dobermann et al. 2017).
- **Eating habits and high standards** for the shape and appearance of food have created expectations by consumers regarding the freshness and look of especially fruits and

[23] Subsidies that are considered to have only minimal effects on trade are exempt from WTO rules to prohibit domestic agricultural support measures that distort trade. Such payments must not be based on current production or market prices, not support higher domestic prices and additionally meet further criteria (World Bank 2020).

vegetables as well as an unlimited choice of all products at any time of the year. This is a driving factor of food loss and waste at international level.

# 4 Recommendations for action

The transformation that is required to change the global food system requires engagement from actors at all levels. In the recommendations outlined in the following sections, aspects like the time frame needed to address the barriers, relevant actors to implement changes, the type of instrument to overcome the barriers, the cost and benefits of overcoming a barrier, ecological and social impacts of overcoming barriers as well as the maturity of options for overcoming barriers are taken into account.

## 4.1 Addressing barriers at farm level

Ultimately, change in agricultural production will be implemented by farmers, farm managers and communities who manage trees, crops, livestock, fields and landscapes. Change in agricultural practices will take place in reaction e.g. to new knowledge, environmental change (e.g. soil degradation, climate change), market demands and new framework conditions (policies, incentives, regulations, restrictions). For that purpose, advice and support to farms need to increase (Mills et al. 2020).

At (small-scale) farm level, **capacity-building is needed in order to disseminate information to local actors and enhance knowledge on the benefits of changing agricultural practices**. For example, to address food loss and waste, agronomic training and education for farmers (as well as other actors along the food chain) is necessary to change practices (HLPE 2014) (see section 2.2.1). Education and outreach on sustainable agricultural practices should be strengthened by government agencies, including approaches to conservation agriculture, practices to increase carbon storage, integrated manure management, approaches to reducing food loss and waste as well as on the appropriate fertiliser application.

In providing training and financial support as incentives to farmers to change agricultural practices, **participatory approaches** appreciating local knowledge and engaging local stakeholders can be beneficial. In that context, knowledge networks play a crucial role. Farmer-to-farmer learning can help to understand the long-term benefits of sustainable agricultural practices and has proven to be particularly important for implementing practices of sustainable intensification, which are highly context-specific and knowledge-intensive. They can thus help to overcome obstructing traditions and habits as well as to accept the short-term costs associated with a change in agricultural practices (Aryal et al. 2020). Programmes and policies to facilitate knowledge transfer should support famers in implementing new practices.

Additionally, **farmers need financial support and the right economic incentives** in order to change agricultural practices. Payments to make up for perceived financial risks can support such changes and incentives should be based on delivering ecosystem services. Microfinancing (or farmer savings groups) may help farmers in the global South to invest if investment is needed for changes in farming practices (Vanlauwe et al. 2014; FAO 2013a). Farmers should be enabled to access and afford the inputs they need to make optimal use of their land resources. Microfinance initiatives providing financial and technological support can also help to address food loss and waste, e.g. by supporting farmers in taking up innovations, adjusting crops to minimise food loss and increasing access to cooling (WWF 2021) (see section 2.2.1).

However, for small-scale (subsistence) farmers, the main focus will be on promoting economic development and resilience to the impacts of climate change. To realise the mitigation potential related to farming by larger producers, policy incentives need to change, which are outlined in the next section.

## 4.2 Addressing barriers at national level

At the national and subnational level, laws and regulations need to be set in the right way to provide incentives to shift production to more sustainable alternatives. Particularly, on a governmental level, **public support needs to be redirected to focus on sustainable practices** (World Bank 2020; Climate Focus; CEA 2014; FAO and UNDP 2021). Financial incentives should be based on ecosystem services instead of being tied to the size of farms or the yield only (Robertson and Vitousek 2009). Direct payments should also be linked to the condition of not clearing new land unless inevitable to guarantee food security (World Bank 2020).

**Agricultural subsidies need to be reformed.** For high-income countries, harmful support needs to be abolished by incorporating conditionality mechanisms in subsidy schemes and avoiding reversals to distorting measures even in times of crisis. Support should not be coupled to production volumes and incentives should particularly be provided for the production of nutritious food for healthy diets. In middle-income countries, subsidies should be decoupled from production or inputs as well and reforms should be accompanied by tailored social protection schemes. Negative effects for low-income groups should be mitigated by appropriate compensatory measures. In low-income countries, additionally, a freer trade and market environment helps to enable higher income for farmers and make the agricultural business more sustainable. Also, increased general support to the sector through investments in R&D for technology improvements and infrastructure have been identified as priority approaches for these countries. Such support should also target the establishment of alternative food products/protein sources and alternative supply chains. Consumer subsidies accompanied by well-designed social protection schemes could support healthy diets in poorer countries. In decoupling payments from production, specific commodities or yields, smallholder farmers can be better targeted as well. Repurposing agricultural support needs to be accompanied by communicating that the shifts are not about reducing support for farmers but re-allocating it in a way that entails greater benefits for society as a whole (FAO and UNDP 2021).

**Targeted support and linking domestic credit lines to policies and best practices** can support producers in moving towards sustainable agricultural production and forest use (Global Canopy Programme 2015) as well as to reduce food waste. To address (perceived) economic risks, public and/or private support should be made available to the transitioning period in which more sustainable practices are implemented (e.g. growing trees in agroforestry systems) (IUCN 2020). Where possible, support should also promote the retirement and restoration of land that is not urgently needed for agricultural purposes. Systems of graduated payments rewarding farmers for increasingly better performance have shown to be more prone to promote climate change mitigation than setting minimum environmental standards. Also, support should enhance innovation by e.g. promoting new technologies that have the potential to become self-sustaining if used more widely (World Bank 2020). Market-based instruments are often mentioned in the literature as a means to incentivise further mitigation action in the agricultural sector (e.g. Smith et al. 2007b; Minasny et al. 2017). However, emission reduction projects that sequester carbon typically cannot guarantee permanent storage of carbon (over a period of hundreds of years, to millennia). This, amongst other risks to their environmental integrity (UBA 2022), undermines their suitability to represent a genuine option for offsetting emissions occurring elsewhere.

Financial incentives should be tied to **environmental requirements** that need to be high, and sufficient money needs to be made available to make a difference. Farm financial aid should be conditioned upon the protection of forests and other native areas. Additionally, conservation funding should support projects that **bring together producers with scientists** to try out innovations, e.g. to reduce fertiliser or pesticide use (Searchinger 2020).

Financial support to shift to more sustainable practices should be aligned with **new, stricter regulations**, e.g. regarding manure management or carbon taxes to reduce GHG emissions from livestock production or fertiliser use (Paustian et al. 2016; Minasny et al. 2017).[24] When designing such incentives, it needs to be ensured that they do not increase overall production output (where this is not needed to ensure food security) or shift emissions to other countries (Thornton et al. 2007). Taxes should send the appropriate signals on the ecological footprint of products to consumers in order to reduce the demand for land-intensive products, particularly meat (Boerema et al. 2016; Sisnowski et al. 2017). Procurement policies provide an additional lever to promote healthy diets implying more sustainable agricultural practices in workplaces, schools and other venues where meals are publicly provided (Willett et al. 2019). **Reforms to improve tenure security** can reduce deforestation and unsustainable agricultural practices, albeit being a sensitive issue (Angelsen 2010; UBA 2021).

Additionally, it is crucial to **send coherent policy signals to the agricultural sector** (OECD 2019a). Climate and environmental effects should be considered in every policy-making that affects agricultural systems. Engagement of subnational food system actors such as farmers, food manufacturers and retailers can help to create strong national frameworks for implementing measures to mitigate emissions from the broader food system (Global Alliance for the Future of Food 2022). Policies are needed that regulate sectoral emissions for the whole land use sector in order to prevent the expansion of production due to improvements in efficiency or increased profits, especially regarding livestock (FAO 2013a). Better coordination between health, agriculture, water and environment departments is also needed to ensure coherence among policies affecting sustainable diets (WRI 2016; FAO and UNDP 2021).

**Monitoring and evaluation of the measures taken** is necessary in order to drive environmental progress and improvements of policy over time (World Bank 2020). Particularly regarding measures to address food loss and waste as well as to address deforestation, better and more effective monitoring and evaluation of the measures/regulation plans are necessary (Global Canopy Programme 2015).

## 4.3 Addressing barriers at the international level

**Multilateral initiatives and summits at the global level need to set the appropriate global framework** for achieving a more sustainable food system through targets, standards and providing a forum for continuous exchange. The UN Food Systems Summits, the Conferences of the Parties (COPs) under the Convention on Biological Diversity (CBD) as well as the UNFCCC bring the global community together to do so (FAO and UNDP 2021).

Furthermore, at the international level, **policies and trade structures need to change** in order to set the right incentives for more sustainable agricultural production. Adjustments to WTO rules might be necessary in order to avoid conflicts between mitigation policies and trade law (Häberli 2018). Taxes have been found to have greater impact on consumption if they are applied in broader regions instead of single countries, if the substitutes are taxed as well and if the taxes are sufficiently high (WRI 2016). The WTO can play a central role in coordinating members to take concerted efforts to reduce distorting agricultural measures while at the same time supporting the transition to sustainable food systems. Also, to address relocation of production to other countries as a result of removing border measures, coherent policies at different levels of governance are needed (FAO and UNDP 2021).

[24] E.g. the US Department of Agriculture programmes include mitigation as a conservation goal; provisons in the EU Common Agricultural Policy link subsidy payments to 'cross-compliance' measures that include maintaining the soil organic carbon content (Louwagie et al. 2011).

Farmers need to be paid **fairer prices** in order to be able to improve harvesting and field management techniques. High levels of subsidies in some countries can depress world prices and thus reduce incomes for other agricultural exporters and local producers. Cartels related to food production and trade as well as financial speculation on food have strong negative effects on populations in low-income countries that depend on global markets (IPCC 2019c). Market regulations and fair trade laws promoting contractual arrangements to share risks more equitably between producers and retailers are therefore necessary, e.g. to empower farmers to address food waste at farm level (WWF 2021). Transparent and inclusive processes with multiple stakeholders as well as strategic communication to promote the goals and benefits of a more sustainable food system are needed to confront vested economic interests (FAO and UNDP 2021). Additionally, financial and technological support to lower-income countries needs to be stepped up to endow local actors with the resources needed to implement mitigation measures.

Particularly to address agricultural expansion and resulting deforestation, a context-specific systems perspective that addresses drivers at all elements of the supply chain is necessary. Holding all actors responsible across the supply chain would need **international regulation** efforts to reduce deforestation (European Parliament 2020; Hughes and Terazono 2020). Developing multilateral public-private partnerships to engage diverse stakeholders while synergising public policies with private zero-deforestation and supply chain initiatives would be one approach to address deforestation (Furumo and Lambin 2020).

Additionally, **more work is needed by the research community to support a sustainable transformation of agriculture**. Firstly, the setting of common definitions, metrics and indicators will help to measure the benefits of approaches to sustainable agriculture (Oberč and Arroyo Schnell 2020; Frison 2020). Otherwise, it will be difficult to monitor progress and uptake of changed land use intensity. Also, the evidence base on the impacts of agricultural support (FAO and UNDP 2021) as well as on measuring the impacts of policies on soil health needs to be further developed (Bispo et al. 2017). Cooperation at international level will be necessary in order to develop standards and guidance for better MRV of emissions related to soils. The experiences on best practices for reducing food waste and losses could be exchanged on a regular and international basis among science and politics to reach global improvement and promote public interest and debate on the issue. Efforts should be pursued to further develop standards for data collection and monitoring and evaluation of food waste and losses across the supply chain (UBA 2021).

## 4.4 Addressing barriers at consumer level

At consumer level, mostly socio-cultural as well as economic barriers play a role. **Education and knowledge as well as societal dialogue processes and guiding principles** are key drivers for overcoming such barriers. Meat analogues such as imitation meat (from plant products), cultured meat and insects may support the shift towards more sustainable diets. Advocacy and education is necessary to promote knowledge on food loss and waste as an incentive to change behaviour. Increasing the variety in our diets can help to reduce incentives for cultivating less suited but very popular plant varieties for specific regions. This needs to be supported by **expanding product specifications** to lower the standards for shape and appearance of food, especially fruits and vegetables at governmental level (WWF 2021). Additionally, **date labelling policies** need to provide clear signals to consumers and can help to cut food waste at consumer level (HLPE 2014).

Furthermore, **technical options could support behavioural changes by consumers**, such as better packaging or the development of “doggy bag” practices in restaurants (HLPE 2014). Food banking by non-governmental initiatives to distribute surplus food can also support efforts to reduce food loss and waste. Governments need to guarantee an institutional environment that favours donations, e.g. by providing the right tax-related incentives and encouraging civil responsibility (HLPE 2014).

Generally, barriers at consumer level to adopting more sustainable, healthy diets are closely linked to broader questions of inequality. It is therefore necessary to make sustainable food more affordable to all consumers as well as to apply "nudging" approaches that direct consumers to make "better choices" (e.g. by providing sustainable choices as defaults or presenting healthier options more attractively) (Reisch et al. 2013). Improving social welfare in general will support efforts to promote a shift towards healthier diets.

# 5 Conclusion

To make agriculture more sustainable and realise emission mitigation potentials identified, as well as other environmental and social co-benefits, the barriers described in this paper will need to be addressed. To do so, it is essential to take a systems perspective in order to involve actors across all governance levels and along the whole supply chain. As a priority, those barriers should be considered which have been identified with sufficiently robust evidence in the literature, are easiest to tackle, are most urgent to change practices with damaging effects to the climate, have largest savings potentials and can be supported by joint international efforts.

As natural, social and economic conditions vary widely across geographies, any measures to enhance mitigation action in the agricultural sector need to be carefully tailored to national or regional needs and circumstances. Foundational information needed in order to develop such measures include:

- Production and consumption trends of crops, including commodity crops, relevant to an economy, as well as associated contributions to, and anticipated impacts from, climate change;
- Production and consumption trends of livestock production and their environmental, economic and cultural relevance within the agricultural sector;
- Trends and potential changes in the structure of agriculture, including the role of large multinational businesses and small-scale producers;
- Land-use changes and the legal context;
- (Changes in) national circumstances, political priorities, development priorities as well as existing climate-related targets and plans on national and subnational levels to ensure policy coherence (WRI; Oxfam 2019: 9f.).

Barriers at the farm level relating to an actual or perceived lack of financial benefit (OECD 2017; Mills et al. 2020) are among the most important barriers to tackle as it will be farmers who are ultimately responsible for implementing changes to agricultural practices. Such barriers exist across all geographical regions. Improving the economic prospect of farms by providing targeted support for more sustainable agricultural practices is one of the most important levers for transforming agricultural production practices. Additionally, providing information, education and capacity building to farmers in order to reduce socio-cultural reservations against changing agricultural practices as well as concerns about negative effects on production is essential to address barriers at farm level.

At national level, a stable agricultural policy oriented at mitigation and adaptation targets is most urgent in order to set the right political incentives and to provide the resources needed to support a sustainable agricultural transformation (OECD 2017). Currently, large amounts of financial support go to the agricultural sector, and to achieve environmental goals, including the mitigation of climate change, it is crucial to make better use of the money available and redirect subsidies in line with environmental targets.

At international level, wrong economic incentives in the global market, low producer prices for food, environmentally harmful agricultural subsidies and a lack of common metrics and indicators remain a challenge to taking a sustainable transformation forward. The global economic system sets a framework for national policy and impacts local farmers in their ability to cover their costs and finance and implement environmental and climate protection measures.

Concerted efforts in multilateral forums are necessary in order to adjust the international framework for promoting the right incentives for action at national level.

To ensure food supply in the context of the consequences of Russia's war against Ukraine, it is essential to prevent price-pushing export restrictions by large agricultural countries, keep trade open and pursue market relaxation (Rudloff and Götz 2022). At the same time, recent reactions by the EU as well as the US to suspend conservation programmes, postpone legislation on nature protection and regulation on pesticides risk putting further pressure on natural resources and biodiversity (Rudloff and Götz 2022; The Greens/EFA 2022). It is now more important than ever to pursue strategies to align food security with the fight against climate change and the erosion of biodiversity at global and national level to achieve a more sustainable food system for all in the future.

Consumers play an important role in tackling emissions from the agricultural sector as they send signals to the market. Behavioural changes are therefore another crucial component in the transformation to a more sustainable food system, particularly for tackling the overconsumption of meat, as well as food loss and waste as structural problems that cannot only be addressed by technical measures.

The barriers to achieve mitigation in the agricultural sector show similar patterns across the globe and yet, the national, regional or local challenges, needs and priorities are different and context-specific. To design effective policies, it is crucial to identify and prioritise existing barriers, identify the relevant actors and entry points to address them, and design appropriate political strategies. Including mitigation targets related to agriculture in countries' NDCs provides an opportunity to raise ambition to mitigate emissions related to food systems. So far, NDCs often focus on food production aspects, leaving demand-side measures to promote dietary changes and tackling food waste aside. Enhancing the engagement of all relevant stakeholders in NDC development processes and aligning agricultural support and other policies with mitigation targets can help to use the NDC process to promote mitigation in the agricultural sector (Global Alliance for the Future of Food 2022).

The means to mitigate emissions from agriculture while at the same time promoting increased food security are there. To achieve a sustainable transformation of our food system, we need to rethink our approach and our attitude to agriculture instead of focusing only on technical solutions. Engagement from governments, companies, producers and consumers is required to do so, supported by an agenda set at the international level.

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