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Final report

Ambitious GHG mitigation opportunities and challenges in the agriculture sector

Analysis of sustainable potentials in selected countries

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Abstract: Ambitious GHG mitigation opportunities and challenges in the agriculture sector

Climate change poses a significant threat to ecosystems and livelihoods, necessitating urgent reductions in greenhouse gas emissions. A substantial portion of global emissions stem from food systems, encompassing crop and livestock production, land use, and the food production value chain. Monocultures and agricultural intensification further exacerbate biodiversity loss, pollution, and strain water resources. Shifting towards plant-based diets and adopting agricultural mitigation measures is vital to align emission levels with the goals of the Paris Agreement and remain within planetary boundaries. This report presents findings of the project "Ambitious GHG Reduction in Agriculture: Analysis of Sustainable Potentials in Selected Priority Countries" (FKZ 3720 41 504 0) regarding key mitigation options for agricultural and food system activities, barriers towards their implementation and solutions for overcoming these, as well as climate change mitigation potentials and barriers within the agricultural sector of ten selected countries. This report also describes the methods (including literature estimates) used to evaluate the mitigation potential of selected measures in each of the countries and the challenges encountered implementing those methods. Examining the mitigation potential and implementation challenges for agricultural mitigation measures across a diverse set of countries underscores the need for tailored solutions to account for unique cultural, geographical, and climatic contexts within the agricultural sector. The findings of this project also underline the vital role of agriculture in climate targets, sustainable development, and food security. A collaborative, global effort is required to shift towards sustainable food systems in the face of growing climate change impacts.

Kurzbeschreibung: Ambitionierte Treibhausgasminderung in der Landwirtschaft: Analyse von nachhaltigen Potenzialen in ausgewählten Schwerpunktländern

Die Klimaerwärmung bedroht Ökosysteme und Lebensgrundlagen und macht eine Verringerung der Treibhausgasemissionen dringend erforderlich. Ein beträchtlicher Teil der globalen Emissionen stammt aus dem Ernährungssystem, das die Pflanzen- und Tierproduktion, die Landnutzung und die Wertschöpfungskette der Lebensmittelproduktion umfasst. Monokulturen und die Intensivierung der Landwirtschaft verschärfen den Verlust der biologischen Vielfalt, die Umweltverschmutzung und die Belastung der Wasserressourcen noch weiter. Die Umstellung auf eine pflanzliche Ernährung und die Einführung von Maßnahmen zur Emissionsminderung in der Landwirtschaft sind von entscheidender Bedeutung, um die Emissionswerte mit den Zielen des Pariser Abkommens in Einklang zu bringen und innerhalb der planetaren Grenzen zu bleiben. Der vorliegende Bericht präsentiert Ergebnisse des Projekts „Ambitionierte THG-Minderung in der Landwirtschaft: Analyse nachhaltiger Potenziale in ausgewählten Schwerpunktländern" (FKZ 3720 41 504 0) in Bezug auf die wichtigsten Minderungsoptionen für Aktivitäten in der Landwirtschaft und im Ernährungssystem, Hemmnisse für die Umsetzung dieser Optionen und Lösungsansätze zu deren Überwindung sowie auf Klimaschutzpotenziale und Barrieren innerhalb des Agrarsektors in zehn ausgewählten Ländern. Dieser Bericht beschreibt auch die Methoden (einschließlich der Verwendung von Vergleichsliteratur), die zur Bewertung des Minderungspotenzials ausgewählter Maßnahmen in jedem der Länder verwendet wurden, sowie die Herausforderungen, die bei der Umsetzung dieser Methoden aufgetreten sind. Die Untersuchung des Minderungspotenzials und der Herausforderungen bei der Umsetzung von Minderungsmaßnahmen in der Landwirtschaft in einer Vielzahl von Ländern unterstreicht die Notwendigkeit maßgeschneiderter Lösungen, die den spezifischen kulturellen, geografischen und klimatischen Gegebenheiten des jeweiligen Agrarsektors Rechnung tragen. Die Ergebnisse dieses Projekts unterstreichen außerdem die entscheidende Rolle der Landwirtschaft für Klimaziele, nachhaltige Entwicklung und Ernährungssicherheit.

Gemeinsame, globale Anstrengungen sind nötig, um unsere Lebensmittelsysteme, nachhaltig zu transformieren.

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AFOLU	Agriculture, Forestry and Other Land Use
AUS	Australia
AWD	Alternate wetting and drying
CAT	Climate Action Tracker
CBD	Convention on Biological Diversity
CGIAR	Consultative Group for International Agricultural Research
CH_4	Methane
CO_2	Carbon dioxide

COP	Conference of Parties
EI	Emission Intensities
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
NDC	Nationally Determined Contributions (in Paris Agreement)
NGHGIs	National Greenhouse Gas Emissions Inventories
NUE	Nitrogen Use Efficiency
NZL	New Zealand
N_2O	Nitrous oxide
MRV	Measurement, reporting and verification
Mt	Megatonne
R&D	Research and Development
SDGs	Sustainable Development Goals
SOC	Soil organic carbon
SRI	System of Rice Intensification
t	tonne
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USD	United States Dollar
WP	Work package
WTO	The World Trade Organization

Summary

Global warming poses a threat to ecosystems and livelihoods, urgently necessitating greenhouse gas emission reductions. The IPCC Special Report estimates that 21–37% of global emissions stem from food systems, encompassing crop and livestock production, land use, and the food production value chain (Shukla et al. 2019). In addition, agricultural intensification and monocultures increasingly contribute to biodiversity loss and water resource strain. Shifting towards plant-based diets and adopting agricultural mitigation measures is crucial to meet the goals of the Paris Agreement and remain within planetary boundaries. The agricultural sector is not only vital for climate targets, but also for sustainable development, underpinning food security, livelihoods, and its poverty reduction potential.

In the project "Ambitious GHG Reduction in Agriculture: Analysis of Sustainable Potentials in Selected Priority Countries" (FKZ 3720 41 504 0), the contractors first supported UBA in administrative-logistical tasks related to the coordination of the EU thematic group on land use during the German Council Presidency in the second half of 2020 and prepared background papers on the land use-related processes under the UNFCCC.[1] In a second part of the project, the barriers to ambitious climate protection in agriculture and approaches to overcome them were analysed (Siemons et al. 2023a). Thirdly, the project examined the agricultural sector of ten selected countries and identified potential for more ambitious climate protection in these countries. This report documents the findings of work package 2 (WP2) and work package 3 (WP3) of the research project.

Mitigation measures in the agricultural sector

The IPCC (Nabuurs et al. 2022) identified a mitigation potential[2] of 11.2 $GtCO_2e$/year (middle value of range) for supply side measure in the agricultural sector. This includes measures to improve carbon sequestration (e.g. agroforestry) and measures to reduce methane and nitrous oxide emissions from enteric fermentation, rice cultivation. The majority of this potential is derived from enhanced carbon sinks and not from emission reductions from agricultural production. On the other hand, 4.2 $GtCO_2e$/year of technical mitigation potential was identified on the demand side by 2050 – mainly from shifting to sustainable healthy diets (Nabuurs et al. 2022). To achieve this mitigation potential, demand-side measures to address dietary habits would need to be supported by political measures to reduce production volumes or livestock numbers (e.g. limiting livestock numbers per). This is especially true for countries which export livestock. The economic mitigation potential[3] for supply side measures from agriculture (incl. carbon sequestration) is estimated to be around 4.1 $GtCO_2e$/year (middle value of range) and around 2.2 $GtCO_2e$/year on the demand side by 2050 at carbon prices up to 100 USD tCO_2 (ibid).

In chapter 2 of this report, the key mitigation options in the agriculture sector are outlined. Mitigation options considered include supply-side as well as demand-side activities. 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 are not on-farm measures are briefly outlined. On the

[1] The papers are available for download at https://www.umweltbundesamt.de/en/topics/climate-energy/ambitious-greenhouse-gas-mitigation-in-agriculture.

[2] The technical mitigation potential is an estimate of greenhouse gas emissions reductions or removals of CO_2 that can be achieved assuming a specific technology or measure is applied wherever feasible. Costs and other constraints, e.g. whether this technology is accepted by users, are not considered.

[3] The economic mitigation potential is estimated considering the cost-effectiveness of specific technologies or measures.

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. We did not quantify the mitigation potential of supply or demand side measures that would lead to a reduction in livestock numbers. However, these measures are highlighted as additional mitigation options particularly in countries where livestock numbers exceed recommended numbers and there is limited potential for efficiency gains.

Key mitigation options explored and described include:

- Supply-side measures
  - Changes in the cultivation system
  - Improved management of nitrogen fertilisers
  - Improved management of livestock manure
  - Reduced emissions from livestock
  - Carbon storage in agricultural systems
  - Reduction of greenhouse gas emissions from rice cultivation
  - Changing burning practices
- Demand-side measures
  - Reducing food waste and losses
  - Changing dietary habits
  - Avoiding deforestation to create arable land and grassland[4]

Potential for ambitious climate action in agriculture in 10 selected countries

Which of these mitigation options are most appropriate varies between countries based on factors such as local climate, main agricultural products, and current agricultural systems. To understand these differences and identify concrete opportunities for mitigation in the sector, we explore the suite of mitigation options in the context of 10 countries; Australia, Argentina, Brazil, China, Egypt, Indonesia, New Zealand, South Africa, United Kingdom, and the United States. For each country, current national circumstances, climate change mitigation potentials, and related barriers in the agricultural sector were analysed, with a focus on interventions on the production side. In this report, we describe the methods (including literature estimates) used to evaluate the mitigation potential of selected measures in each of the countries and the challenges encountered implementing those methods. We also outline some of the similarities and differences in challenges faced by these countries, and ideas of how these challenges could be overcome. Detailed results are presented in a separate dossier for each country. [5]

[4] This is included under the demand side measures, because the report addresses the impact of agriculture, and it the demand for agricultural commodities that is a key driver of deforestation.

[5] The country papers are available at: https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-australia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-brazil; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-china; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-egypt; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-indonesia;

For each of the 10 individual countries, we first examined the national circumstances and current mitigation plans with the goal of identifying where there is additional mitigation potential. In order to do so, a qualitative analysis of the characteristics and circumstances of the agricultural sector in each of the selected countries was conducted based on existing emission profiles for agricultural activities, the socio-economic background, trade and employment data, current national climate policies, vulnerability of the agricultural sector to the impacts of global warming and food consumption and waste trends (see section 3.2.2). These country profiles informed the quantitative and qualitative analysis of GHG mitigation potentials for selected key measures to ensure the relevance and integrity of the resulting recommendations. The options identified are analysed in terms of their contribution to national and global food security goals, climate resilience and adaptive capacity. Furthermore, barriers towards implementing these measures and approaches to overcome these barriers are presented. All country-specific analyses follow a common methodological framework to ensure both comparability of results and consistency of conclusions and recommendations for action.

Agriculture sector characteristics and main emissions sources

The role of agriculture in the economy varies substantially across the 10 countries studied, but most of the countries studied view the agricultural sector as critical to foreign export earnings and in some countries, agriculture made up over half of export revenues (e.g. Argentina). Employment in agriculture also considerably varies across the countries, with mechanisation leading to lower employment rates in countries like the US, the UK, Australia, and Argentina, in contrast to Indonesia, Egypt, and China, where agriculture still employs at least a quarter of the workforce, albeit with a decreasing trend.

Over the past few decades, the agricultural sector has become increasingly consolidated, favouring large-scale operations. This trend has significant implications for rural development and poverty reduction, particularly in developing countries aiming to shift from subsistence to commercial farming. Land dedicated to agriculture is substantial across most of the countries studied, often with significant pasture area for livestock grazing.

The agricultural sector and water security are highly interlinked, especially in water-scarce countries such as South Africa, Australia and Egypt. The agricultural sector is responsible for most water use in these countries, which has led to some controversies in how the resources are distributed.

Emission sources in agriculture differ by country, but common patterns emerge, with enteric fermentation, manure management, manure deposited on agricultural land, and on-farm energy use being the most substantial contributors to agricultural emissions across all countries, with enteric fermentation commonly being the largest source. In countries where rice is a staple food and extensively grown, emissions from rice cultivation are a major share of total agricultural emissions (e.g. China, Indonesia, Egypt). Emissions from crop production are predominantly derived from synthetic fertiliser use. In most of the countries analysed, farmers currently overapply fertiliser to their fields, which is driven in part by its low cost from government subsidies, resulting in significant nutrient losses and corresponding environmental pollution and emissions.

https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-new-zealand;
https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-south-africa;
https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-uk;
https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-usa.

In some cases, LULUCF emissions can completely overshadow agricultural emissions. Land-use change emissions are generally driven by deforestation for agricultural expansion and includes the drainage and burning of peatlands in the case of Indonesia. Of the ten countries we examined, deforestation emissions are particularly relevant for Indonesia and Brazil, but also Argentina and the USA.

The governance structure and climate change policy framework of the agricultural sector is very different across countries. In some cases, the agricultural mitigation activities are implemented by the relevant environmental department or ministry, while other countries put the responsibility onto the agriculture (or agribusiness) ministry. Most of the countries do not include a sectoral target for the agricultural sector in their NDC. In general, many of the countries' current climate pledges are incompatible with a 1.5 emissions pathway. Several countries have sectoral climate plans for agriculture, but these often lack emphasis on changing production methods or diets.

External factors like food waste, dietary habits, the COVID-19 pandemic, and climate change highly influence agricultural practices and emissions. For instance, many of the countries in this study are top consumers of animal products, although ruminant meat consumption has usually declined in favour of poultry.

Climate change poses a substantial risk to the agricultural sector. Australia, South Africa, China and Argentina have all faced droughts in recent years, which affected yields and caused considerable livestock deaths. Drought episodes, other natural disasters (e.g. floods), and pest outbreaks are expected to become more frequent as global temperature increases. Crop production will likely be displaced across regions as general climactic conditions change. Livestock systems across countries are vulnerable to heat stress, affecting their productivity and profitability. Most countries have developed a national adaptation strategy, which cite regenerative agricultural practices as an important adaptation component.

Identifying key opportunities for mitigation in each country

Measures to reduce and avoid greenhouse gas emissions from Agriculture, Forestry and Other Land Uses (AFOLU) are diverse and can target both the supply and demand of agricultural goods (such as grain, meat and dairy products, timber, etc.). The relevance and potential of individual measures varies both regionally and nationally. These depend, among other things, on the key products from the agricultural sector, the degree of intensification of production systems, agri-climatic conditions and adaptation needs, cultural and socio-economic conditions, and the nature of agricultural trade. Particularly, any mitigation measure must be considered in the context of national development priorities in countries in which food security is not ensured for the whole population. Recommendations for effective mitigation measures must therefore be appropriate and tailored to national circumstances.

Three main elements contribute to the areas in which the most mitigation potential lies in a country: firstly, the main emission sources in the country and, secondly, the footprint of existing agricultural systems in terms of emission intensities (tCO_2e/tonne of product) and thirdly, the sustainability of the production systems. Intensive production systems often require high inputs that cause emissions in other sectors (e.g. fertiliser production, on-farm energy use) or result in higher indirect emissions from increased fertiliser application and/or livestock grain feed production, including land use emissions from deforestation. It is equally important to consider the environmental, economic, and social co-benefits that arise from certain mitigation options.

Examining the mitigation potential and implementation challenges for agricultural mitigation measures across a diverse set of countries underscores the need for tailored solutions to account for unique cultural, geographical, and climatic contexts within the agricultural sector. The country reports assess potential mitigation strategies for various agricultural activities, aiming to address large-scale agribusiness and subsistence farming alike.

Evaluating mitigation potential

We find that stopping agricultural expansion, a leading cause for deforestation particularly in tropical countries (e.g. Brazil and Indonesia), has the highest impact on emissions. Nonetheless, reducing emissions from enteric fermentation also has a significant mitigation potential, especially demand-side measures to reduce domestic consumption of animal products. Enteric fermentation is a key emission source, in most countries, including transition economies with high dependencies on exports of animal products. Such measures would reduce total livestock numbers and must be supported by additional policies and targets that lead to an overall reduction of livestock production, e.g. through compensating farmers or limiting livestock numbers per area. This is especially important in countries that have high numbers of livestock, either because they export livestock products or because they have a high consumption of livestock. However, this is contrary to political aims to increase livestock production, may tackle sensitive national circumstances (cultural consumption patterns, threats to food security etc.) and thus faces substantial economic, political and socio-economic barriers. Nevertheless, emissions from enteric fermentation and other livestock-related emissions are difficult to fully mitigate if production volumes are not changed. We find that in many cases, the targeted increase in livestock production in the future would offset any emissions reductions from improved livestock management and feed systems (e.g. Australia and Argentina).

While the mitigation potential of certain agroecological practices like cover crops and crop rotation is estimated to be rather limited based on the literature, they provide numerous co-benefits, including adaptation to climate change impacts, and are no-regret measures that can be widely implemented.

While land-based mitigation measures that increase carbon sequestration on agricultural land are an attractive option that can have quite high sequestration potential (e.g. grassland restoration, agroforestry/silvopastoralism), there are many risks and uncertainties as to their effective implementation. Natural carbon sequestration measures should not replace the decarbonisation needed in the agricultural sector to meet climate targets and 1.5°C compatible emission levels. However, due to their numerous co-benefits, and their effectiveness as a climate change adaptation measure, they should continue to be supported and implemented.

While this project focuses on mitigation in agricultural production, it is essential to highlight that without changes in dietary patterns and accompanying reduction of livestock, mainly in developed countries, a sustainable 1.5°C pathway is not feasible. Discussing alternative narratives could help understand the implications of a shift to largely plant-based diets and potentially avoid disruptions in the sector in the medium to long term. Food waste causes unnecessary GHG emissions through the agricultural production of unused food products and through methane emissions from waste management. Thus, reducing food waste levels across the supply chain could result in significant avoided emissions. International research reports show that demand-side measures, such as shifting to less meat-intensive diets and reducing food waste, have a high mitigation potential while contributing to other co-benefits at relatively lower costs.

Barriers for ambitious mitigation

The IPCC Special Report on Climate Change and Land 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 foods, 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.

A myriad of different barriers obstruct mitigation in the agricultural sector. These barriers can be clustered according to the relevant governance level for taking action, while taking into account the IPCC classification of barriers as outlined above.

At the farm level, economic barriers include a lack of specific economic benefits to the farm for mitigation action. Changes can imply high adoption costs to the farmer. Coupled with a lack of access to credits or other financial resources and uncertainty regarding the long-term economic benefits of mitigation action, the incentive to take risks and modify existing practices can be low. Additional farm-level barriers include land-tenure insecurity, lack of advice or information, and the need to change personal attitudes, traditions, and practices.

National priorities and policies can support or hinder mitigation. Some resistance to mitigation may be driven by perceived potential negative effects on production, and competition with economic objectives to increase agricultural output. Even where national goals align with mitigation, existing policies to support production, such as input subsidies or tax exemptions, may hinder action.

Barriers to mitigation at the international level include the possibility of carbon leakage between countries with different mitigation policies and the challenge of tackling emissions through long supply chains, including those linked to deforestation, that have many actors involved. Asymmetric trade structures and power imbalances can increase the economic vulnerability of farmers, making it more difficult to adopt new practices.

Finally, consumer preferences rooted in social and cultural habits, such as diets with high meat content or preferences for food with certain shape and appearances pose challenges to shifting to sustainable diets and reducing food waste.

Overcoming barriers to mitigation in the selected countries

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 vary and are context-specific. Common challenges on the farm-level include farmers' lack of awareness about mitigation options and limited access to upfront financing. Disseminating knowledge on sustainable practices alongside accessible financial incentives can help address such barriers. Engaging local stakeholders and valuing indigenous knowledge through participatory approaches can further encourage adoption of sustainable practices. Farmer-to-farmer learning stands out as a crucial avenue to implement context-specific sustainable production practices.

In many of the analysed countries, agricultural policies, including production targets and striving for self-sufficiency, are currently decoupled from climate targets, and are often managed by different ministries. Integrating climate goals into agricultural production plans could enhance mitigation efforts and bolster the sector's resilience against worsening climate impacts. The involvement of a diverse set of stakeholders, including farmers, manufacturers, retailers, and local and national governments, can establish robust national frameworks for curbing emissions across the broader food system.

Sector-wide emission regulations are necessary to prevent production expansion driven by efficiency gains, particularly in the livestock sector. Improved coordination between the health, agriculture, water, and environment ministries is vital to harmonise policies promoting sustainable diets. Aligning agricultural subsidies with sustainability and quality, rather than output, is crucial. Financial incentives for sustainable practices should adhere to strict regulations, avoiding unintended production growth or emissions leakage. Economic instruments (i.e. taxes, subsidies) could reflect products' ecological impact to reduce demand for resource-intensive items, such as meat. Procurement policies can also steer diets towards sustainability in public spaces, while land tenure reforms have the potential to combat deforestation and unsustainable practices.

To overcome international-level barriers to achieving sustainable food systems, it is essential for multilateral initiatives and global summits to establish a comprehensive framework through targets, standards, and ongoing discussions. Notably, events like the UN Food Systems Summits and the Conferences of the Parties (COPs) under the Convention on Biological Diversity (CBD) and UNFCCC serve as platforms for collective action. Agricultural policies and trade structures must also be reformed on an international scale to incentivise more sustainable agricultural practices, including ensuring fairer prices for farmers, countering negative impacts from food-related cartels and financial speculation that affect vulnerable populations in low-income nations, and implementing market regulations and fair-trade laws which distribute risks more equitably among producers and retailers. Moreover, addressing challenges like agricultural expansion and deforestation necessitates a context-specific, holistic approach that engages all supply chain stakeholders. International regulations are required to curb deforestation, while the creation of multilateral public-private partnerships can harness the synergy between public policies and private initiatives combatting deforestation.

Meanwhile, at the consumer level, a broader societal transformation is required. Educational campaigns, open dialogues, and measures to make sustainable food more affordable can help overcome the socio-cultural and economic barriers that hinder the adoption of sustainable diets.

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. 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 stellt eine Bedrohung für Ökosysteme und Lebensgrundlagen dar und macht die Reduzierung der Treibhausgasemissionen dringend erforderlich. Der IPCC-Sonderbericht schätzt, dass 21-37% der weltweiten Emissionen aus Nahrungsmittelsystemen stammen, die Ackerbau und Viehzucht, die Landnutzung und die Wertschöpfungskette der Lebensmittelproduktion umfassen (Shukla et al. 2019). Darüber hinaus tragen landwirtschaftliche Intensivierung und Monokulturen zunehmend zum Verlust der Artenvielfalt und zur Belastung der Wasserressourcen bei. Eine Umstellung auf pflanzenbasierte Ernährung und die Umsetzung landwirtschaftlicher Maßnahmen zur Emissionsminderung sind entscheidend, um die Ziele des Pariser Abkommens zu erreichen und innerhalb der planetaren Grenzen zu bleiben. Der Agrarsektor ist nicht nur für die Klimaziele von großer Bedeutung, sondern auch für nachhaltige Entwicklung durch die Unterstützung von Ernährungssicherheit, Lebensgrundlagen und das Potenzial zur Armutsreduktion.

Im Projekt "Ambitionierte THG-Minderung in der Landwirtschaft: Analyse nachhaltiger Potenziale in ausgewählten Schwerpunktländern" (FKZ 3720 41 504 0) unterstützten die Auftragnehmer zunächst das UBA bei administrativen und logistischen Aufgaben im Zusammenhang mit der Koordination der EU-Themengruppe zur Landnutzung während der deutschen Ratspräsidentschaft in der zweiten Hälfte des Jahres 2020 und bereiteten Hintergrundpapiere zu landnutzungsbezogenen Prozessen im Rahmen der UNFCCC vor[6]. Im zweiten Teil des Projekts wurden die Hindernisse für ehrgeizigen Klimaschutz in der Landwirtschaft und Ansätze zu ihrer Überwindung analysiert (Siemons et al. 2023b). Drittens untersuchte das Projekt den Agrarsektor von zehn ausgewählten Ländern und identifizierte Potenziale für einen ambitionierteren Klimaschutz in diesen Ländern. Dieser Bericht dokumentiert die Ergebnisse von Arbeitspaket 2 (AP2) und Arbeitspaket 3 (AP3) des Forschungsprojekts.

Maßnahmen zur Emissionsminderung im Agrarsektor

Für den Agrarsektor hat der IPCC (Nabuurs et al. 2022)ein technisches Minderungspotenzial von 11,2 GtCO_2e/Jahr (Mittelwert des Bereichs) auf der Produktionsseite durch Kohlenstoffbindung (z. B. Agroforstwirtschaft) und globale Maßnahmen zur Reduzierung von Methanemissionen aus der enterischen Fermentation, dem Reisanbau, etc. und Stickstoffemissionen aus der Düngung identifiziert. Der Großteil dieses Potenzials resultiert dabei aus verbesserten Kohlenstoffsenken. Andererseits wurde bis 2050 ein technisches Minderungspotenzial von 4,2 GtCO_2e/Jahr auf der Nachfrageseite identifiziert, hauptsächlich durch den Übergang zu nachhaltigen, gesunden Ernährungsweisen. Um dieses Minderungspotenzial zu erreichen, müssten nachfrageseitige Maßnahmen zur Änderung der Ernährungsgewohnheiten durch politische Maßnahmen zur Verringerung der Produktionsmengen/Viehbestände (z. B. Begrenzung des Viehbestands pro Fläche) unterstützt werden. Das wirtschaftlich umsetzbare Minderungspotenzial wird bis 2050 auf etwa 4,1 GtCO_2e/Jahr (Mittelwert der Spannweite der Schätzungen) aus der Landwirtschaft (einschließlich Kohlenstoffbindung) und etwa 2,2 GtCO_2e/Jahr auf der Nachfrageseite bei CO_2-Preisen von bis zu 100 USD pro tCO_2 geschätzt (ibid).

Im zweiten Kapitel dieses Berichts werden die wichtigsten Minderungsoptionen im Agrarsektor skizziert. Berücksichtigte Minderungsoptionen umfassen Aktivitäten auf der Angebotsseite sowie auf der Nachfrageseite. Auf der Angebotsseite fokussieren wir uns auf jene Optionen, die direkt mit landwirtschaftlichen Praktiken in Verbindung stehen und auf der Betriebsebene

[6] Die Papiere sind verfügbar unter https://www.umweltbundesamt.de/en/topics/climate-energy/ambitious-greenhouse-gas-mitigation-in-agriculture.

umgesetzt werden können, dazu gehören die Vorbereitung und Bewirtschaftung von Land, die Auswahl und Vielfalt der Nutzpflanzen, verwendete Technologien sowie der Ernteprozess. Der Energieverbrauch im Agrarsektor und die Herstellung von Düngemitteln als Minderungsoptionen, die mit dem breiteren landwirtschaftlichen System zusammenhängen, jedoch keine Maßnahmen auf dem Betrieb darstellen, werden kurz skizziert. Auf der Nachfrageseite schließen wir Maßnahmen, die die landwirtschaftliche Produktion direkt beeinflussen, mit ein. Die nachfolgenden Phasen des Transportes, der Verteilung, der Verarbeitung und des Einzelhandels von landwirtschaftlichen Gütern waren bewusst nicht Teil der Analyse. Wir haben keine Maßnahmen zur direkten Verringerung des Viehbestands auf der Produktionsseite in Betracht gezogen, sondern betrachten dies eher als Ergebnis von Maßnahmen auf der Nachfrageseite, um Verlagerungseffekte zu vermeiden. Maßnahmen zur Verringerung des Viehbestands oder zur Änderung der Ernährungsgewohnheiten werden jedoch als zusätzliche Minderungsoptionen hervorgehoben.

Die untersuchten und beschriebenen Schlüssel-Minderungsoptionen umfassen:

- Maßnahmen auf der Angebotsseite
- Veränderungen in der Anbauweise
- Verbessertes Management von Stickstoffdüngern
- Verbessertes Management von Nutztierdung
- Reduzierung der Emissionen aus der Tierhaltung
- Kohlenstoffspeicherung in landwirtschaftlichen Systemen
- Reduzierung der Treibhausgasemissionen aus dem Reisanbau
- Veränderung von Verbrennungspraktiken
- Maßnahmen auf der Nachfrageseite
- Reduzierung von Lebensmittelverschwendung und -verlusten
- Änderung der Ernährungsgewohnheiten
- Reduzierung von Entwaldung zur Schaffung von Ackerland und Weideland

Potenzial für ambitionierte Klimaschutzmaßnahmen in der Landwirtschaft in 10 ausgewählten Ländern

Welche der Minderungsoptionen am meisten geeignet sind, variiert je nach Land und hängt von Faktoren wie lokalem Klima, Hauptprodukten der Landwirtschaft und bestehenden landwirtschaftlichen Systemen ab. Um diese Unterschiede zu verstehen und konkrete Möglichkeiten zur Minderung im Sektor zu identifizieren, untersuchen wir verschiedene Minderungsoptionen im Kontext von 10 Ländern: Australien, Argentinien, Brasilien, China, Ägypten, Indonesien, Neuseeland, Südafrika, Vereinigtes Königreich und Vereinigte Staaten. Für jedes Land wurden aktuelle nationale Gegebenheiten, das Potenzial zur Minderung des Klimawandels und damit verbundene Hindernisse im Agrarsektor analysiert, wobei der Fokus auf Interventionen auf der Produktionsseite lag. In diesem Bericht beschreiben wir die Methoden (einschließlich Literatureinschätzungen), die zur Bewertung des Minderungspotenzials ausgewählter Maßnahmen in jedem der Länder verwendet wurden, und die bei der Implementierung dieser Methoden aufgetretenen Herausforderungen. Wir skizzieren zudem einige der Ähnlichkeiten und Unterschiede in den Herausforderungen, denen sich diese Länder gegenübersehen, und Ideen, wie diese Herausforderungen bewältigt werden könnten. Detaillierte Ergebnisse werden in einem separaten Bericht für jedes Land präsentiert.[7]

Für jedes der 10 einzelnen Länder haben wir zunächst die nationalen Gegebenheiten und aktuellen Minderungspläne untersucht, um festzustellen, wo zusätzliches Minderungspotenzial vorhanden ist. Um dies zu erreichen, wurde eine qualitative Analyse der Merkmale und Umstände des Agrarsektors in jedem der ausgewählten Länder durchgeführt, basierend auf vorhandenen Emissionsprofilen für landwirtschaftliche Aktivitäten, sozioökonomischen Hintergrund, Handels- und Beschäftigungsdaten, aktuellen nationalen Klimapolitiken, der Anfälligkeit des Agrarsektors für die Auswirkungen der globalen Erwärmung sowie Trends bei Lebensmittelkonsum und -verschwendung (siehe Abschnitt 3.2.2). Diese Länderprofile lieferten wichtige Hintergrundinformationen für die quantitative und qualitative Analyse der Potenziale zur Reduzierung von Treibhausgasen für ausgewählte Schlüsselmaßnahmen, um die Relevanz und Integrität der resultierenden Empfehlungen sicherzustellen. Die identifizierten Optionen werden hinsichtlich ihres Beitrags zu nationalen und globalen Zielen für die Ernährungssicherheit, Klimaresilienz und Anpassungsfähigkeit analysiert. Außerdem werden Barrieren zur Umsetzung der Maßnahmen und Ansätze zur Überwindung dieser Barrieren skizziert. Alle länderspezifischen Analysen folgen einem gemeinsamen methodischen Rahmen, um sowohl die Vergleichbarkeit der Ergebnisse als auch die Konsistenz der Schlussfolgerungen und Empfehlungen für Maßnahmen sicherzustellen.

Merkmale des Agrarsektors und Hauptquellen von Emissionen

Die Rolle der Landwirtschaft in der Wirtschaft variiert erheblich in den untersuchten 10 Ländern, aber die meisten dieser Länder betrachten den Agrarsektor als entscheidend für Exporteinnahmen. In einigen Ländern machte die Landwirtschaft sogar mehr als die Hälfte der Exporteinnahmen aus (z. B. Argentinien). Die Beschäftigung in der Landwirtschaft variiert ebenfalls erheblich zwischen den Ländern, wobei ein hoher Grad an Industrialisierung zu niedrigeren Beschäftigungsquoten in Ländern wie den USA, dem Vereinigten Königreich, Australien und Argentinien führt, im Gegensatz zu Indonesien, Ägypten und China, wo die Landwirtschaft immer noch mindestens ein Viertel der Arbeitskräfte beschäftigt, wenn auch mit einem abnehmenden Trend.

In den letzten Jahrzehnten ist der Agrarsektor zunehmend konsolidiert worden und begünstigt groß angelegte Betriebsführung. Diese Entwicklung hat erhebliche Auswirkungen auf die ländliche Entwicklung und die Armutsbekämpfung, insbesondere in Entwicklungsländern, die den Übergang von der Subsistenzwirtschaft zur kommerziellen Landwirtschaft anstreben. Die für die Landwirtschaft genutzte Fläche ist in den meisten der untersuchten Länder erheblich, oft mit erheblichen Weideflächen für die Nutztierhaltung.

Der Agrarsektor und die Wassersicherheit sind eng miteinander verknüpft, insbesondere in wasserarmen Ländern wie Südafrika, Australien und Ägypten. Der Agrarsektor ist für die

[7] Die Papiere sind verfügbar unter: https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-argentina; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-australia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-brazil; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-china; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-egypt; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-indonesia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-new-zealand; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-south-africa; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-uk; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-usa..

Mehrheit der Wasserentnahme in diesen Ländern verantwortlich, was zu Kontroversen darüber geführt hat, wie die Ressourcen verteilt werden.

Emissionsquellen in der Landwirtschaft unterscheiden sich je nach Land, aber es ergeben sich gemeinsame Muster, wobei Emissionen aus der Tierhaltung (enterische Fermentation), Güllemanagement, auf landwirtschaftlichem Land ausgebrachte Gülle und der Energieverbrauch auf dem Betrieb die bedeutendsten Beiträge zu den landwirtschaftlichen Emissionen in allen Ländern sind und Fermentation häufig die größte Quelle ist. In Ländern, in denen Reis ein Grundnahrungsmittel ist und umfangreich angebaut wird, machen Emissionen aus dem Reisanbau einen großen Anteil der gesamten landwirtschaftlichen Emissionen aus (z. B. China, Indonesien, Ägypten). Emissionen aus der Pflanzenproduktion stammen hauptsächlich aus der Verwendung von synthetischen Düngemitteln. In den meisten der analysierten Länder überdüngen Landwirte derzeit ihre Felder, auch aufgrund der niedrigen Kosten von Düngemitteln durch staatliche Subventionen, was zu erheblichen Nährstoffverlusten und entsprechender Umweltverschmutzung und Emissionen führt.

In einigen Fällen können LULUCF-Emissionen die landwirtschaftlichen Emissionen völlig überschatten. Emissionen aus Landnutzungsänderungen werden im Allgemeinen durch die Entwaldung zur Ausweitung der Landwirtschaft angetrieben und umfassen die Trockenlegung und Verbrennung von Mooren im Fall von Indonesien. Von den zehn von uns untersuchten Ländern sind die Emissionen aus der Entwaldung besonders relevant für Indonesien und Brasilien, aber auch für Argentinien und die USA.

Die Regierungsstrukturen und der Rahmen für die Klimapolitik im Agrarsektor sind in den verschiedenen Ländern sehr unterschiedlich. In einigen Fällen werden die Minderungsmaßnahmen in der Landwirtschaft von der zuständigen Umweltbehörde oder dem Umweltministerium umgesetzt, während andere Länder die Verantwortung dem Landwirtschafts- (oder Agrarindustrie-) Ministerium übertragen. Die meisten Länder haben kein Sektorziel für den Agrarsektor in ihren NDCs. Allgemein sind viele der aktuellen Klimaversprechen der Länder nicht mit einem Emissionspfad von 1,5 Grad vereinbar. Einige Länder haben sektorale Klimapläne für die Landwirtschaft, doch diese adressieren oft nicht die Änderung von Produktionsmethoden oder Ernährungsgewohnheiten.

Externe Faktoren wie Lebensmittelverschwendung, Ernährungsgewohnheiten, die COVID-19-Pandemie und der Klimawandel beeinflussen stark landwirtschaftliche Praktiken und Emissionen. Zum Beispiel sind viele der in dieser Studie untersuchten Länder führende Verbraucher von Tierprodukten, obwohl der Verzehr von Wiederkäuerfleisch normalerweise zugunsten von Geflügel gesunken ist.

Der Klimawandel stellt ein erhebliches Risiko für den Agrarsektor dar. Australien, Südafrika, China und Argentinien haben in den letzten Jahren alle Dürreperioden erlebt, die die Erträge beeinträchtigen und erhebliche Verluste bei Nutztieren verursacht haben. Dürreperioden, andere Naturkatastrophen (z. B. Überschwemmungen) und Schädlingsausbrüche werden voraussichtlich häufiger auftreten, wenn die globale Temperatur steigt. Die Getreideproduktion kann sich in andere Regionen verlagern, da sich die allgemeinen klimatischen Bedingungen ändern. Nutztiersysteme in verschiedenen Ländern sind anfällig für Hitzestress, der ihre Produktivität und Rentabilität beeinträchtigt. Die meisten Länder haben eine nationale Anpassungsstrategie entwickelt, in der regenerative landwirtschaftliche Praktiken als wichtiger Bestandteil der Anpassung genannt werden.

Identifizierung zentraler Möglichkeiten zur Minderung in jedem Land

Maßnahmen zur Reduzierung und Vermeidung von Treibhausgasemissionen im AFOLU Sektor sind vielfältig und können sowohl auf das Angebot als auch auf die Nachfrage nach landwirtschaftlichen Gütern (wie Getreide, Fleisch und Milchprodukte, Holz usw.) abzielen. Die Relevanz und das Potenzial einzelner Maßnahmen variieren sowohl regional als auch national. Diese hängen unter anderem von den Hauptprodukten des Agrarsektors, dem Grad der Intensivierung von Produktionssystemen, agroklimatischen Bedingungen und Anpassungsbedarf, kulturellen und sozioökonomischen Bedingungen sowie der Art des landwirtschaftlichen Handels ab. Insbesondere muss jede Minderungsmaßnahme im Kontext der nationalen Entwicklungsprioritäten in Ländern betrachtet werden, in denen die Ernährungssicherheit für die gesamte Bevölkerung nicht gewährleistet ist. Empfehlungen für wirksame Minderungsmaßnahmen müssen daher angemessen und auf die nationalen Gegebenheiten zugeschnitten sein.

Drei Hauptfaktoren bestimmen, wo das größte Minderungspotenzial in einem Land liegt: Erstens die Hauptquellen von Emissionen im Land, zweitens der Fußabdruck der bestehenden landwirtschaftlichen Systeme in Bezug auf ihre Emissionsintensitäten (tCO_2e/Tonne Produkt) und drittens die Nachhaltigkeit der Produktionssysteme. Intensive Produktionssysteme erfordern oft hohe Inputs, die Emissionen in anderen Sektoren verursachen (z. B. Düngemittelproduktion, Energieverbrauch auf dem Betrieb) oder zu höheren indirekten Emissionen durch vermehrte Düngemittelanwendung und/oder Futtermittelproduktion für die Nutztierhaltung führen, einschließlich Emissionen von Landnutzung durch Entwaldung. Es ist ebenso wichtig, die Umwelt-, Wirtschafts- und Sozialvorteile zu berücksichtigen, die sich aus bestimmten Minderungsoptionen ergeben.

Die Untersuchung des Minderungspotenzials und der Umsetzungsherausforderungen für landwirtschaftliche Minderungsmaßnahmen in einer vielfältigen Gruppe von Ländern unterstreicht die Notwendigkeit maßgeschneiderter Lösungen, um den jeweiligen spezifischen kulturellen, geografischen und klimatischen Kontexten im Agrarsektor Rechnung zu tragen. Die Länderberichte bewerten potenzielle Minderungsstrategien für verschiedene landwirtschaftliche Aktivitäten, mit dem Ziel, sowohl Großbetriebe als auch Subsistenzlandwirtschaft in den Blick zu nehmen.

Bewertung des Minderungspotenzials

Wir stellen fest, dass die Beendigung der landwirtschaftlichen Expansion, welche zur Entwaldung, insbesondere in tropischen Ländern (z. B. Brasilien und Indonesien) führt, das größte Minderungspotential hat. Nichtsdestotrotz birgt auch die Verringerung der Emissionen aus der enterischen Fermentation ein erhebliches Minderungspotenzial mit sich, insbesondere durch nachfrageseitige Maßnahmen zur Verringerung des inländischen Verbrauchs von tierischen Produkten. Die enterische Fermentation ist in den meisten Ländern, einschließlich der Schwellenländer, die stark von der Ausfuhr tierischer Erzeugnisse abhängig sind, eine wichtige Emissionsquelle. Solche Maßnahmen würden den Gesamttierbestand verringern und müssen durch zusätzliche politische Maßnahmen und Ziele unterstützt werden, die zu einer allgemeinen Verringerung der Tierproduktion führen, z. B. durch Entschädigung der Landwirte oder Begrenzung des Tierbestands pro Fläche. Derzeit stehen diese Maßnahmen jedoch im Widerspruch zu politischen Zielen in mehreren Ländern, die Viehzucht zu steigern und können heikle nationale Bedingungen (kulturelle Konsummuster, Ernährungssicherheit usw.) betreffen. Daher stehen ihnen erhebliche wirtschaftliche, politische und sozioökonomische Hindernisse im Wege. Dennoch ist es schwierig, die Emissionen aus der enterischen Fermentation und andere tierhaltungsbedingte Emissionen vollständig zu reduzieren, wenn die Produktionsmengen nicht reduziert werden. Wir stellen fest, dass in vielen Fällen der angestrebte Anstieg der Tierproduktion in der Zukunft jegliche Bemühungen, die Emissionsintensität durch verbesserte Tierhaltung und Fütterungssysteme zu reduzieren, ausgleichen würde (z. B. in Australien und Argentinien).

Während das Minderungspotenzial bestimmter agrarökologischer Praktiken wie Deckfrüchte und verbesserte Fruchtfolge auf der Grundlage der Literatur als eher begrenzt eingeschätzt wird, bieten sie jedoch zahlreiche Zusatznutzen, indem sie z.B. die Anpassung an die Auswirkungen des Klimawandels fördern, und sind Maßnahmen, die ohne wesentliche Nachteile in großem Umfang umgesetzt werden können.

Landbasierte Minderungsmaßnahmen, die die Kohlenstoffvorräte auf landwirtschaftlichen Flächen erhöhen, sind eine attraktive Option für den Klimaschutz und haben ein recht hohes Potenzial, zusätzliche Senken zu schaffen (z. B. Wiederherstellung von Grasland, Agroforstwirtschaft/Silvopastoralismus). Es bestehen jedoch viele Risiken und Unsicherheiten hinsichtlich ihrer effektiven Umsetzung. Aktivitäten zur Speicherung von Kohlenstoff in Biomasse sollten die Dekarbonisierung, die im Agrarsektor zur Erreichung von Klimazielen und emissionskompatiblen Werten von 1,5°C erforderlich ist, nicht ersetzen. Weil sie aber zahlreiche Zusatznutzen mit sich bringen und zur Anpassung an den Klimawandel beitragen können, sollten sie jedoch weiterhin unterstützt und implementiert werden.

Obwohl dieses Projekt auf die Minderung in der landwirtschaftlichen Produktion abzielt, ist es unerlässlich zu betonen, dass ohne Änderungen der Ernährungsmuster, hauptsächlich in industrialisierten Ländern, ein nachhaltiger Pfad zur Begrenzung der Erwärmung auf 1,5°C nicht realisierbar ist. Alternative Narrative könnten dazu beitragen, besser zu verstehen, wie ein Übergang zu einer weitgehend pflanzlichen Ernährungsweise aussehen könnte und mögliche Verwerfungen im Sektor mittel- bis langfristig vermeiden. Darüber hinaus verursacht Lebensmittelverschwendung durch ungenutzte Lebensmittel und Methanemissionen aus der Abfallwirtschaft unnötige Treibhausgasemissionen. Daher könnte die Reduzierung von Lebensmittelverschwendung entlang der gesamten Lieferkette erhebliche Mengen an Emissionen vermeiden. Internationale Forschungsberichte zeigen, dass Maßnahmen auf der Nachfrageseite, die weniger fleischintensiven Ernährungsweisen fördern und die Verschwendung von Lebensmitteln reduzieren, ein hohes Minderungspotenzial haben und gleichzeitig zusätzliche Nutzen bei vergleichsweise niedrigeren Kosten mit sich bringen.

Barrieren für ambitionierte THG-Minderung

Der Sonderbericht des IPCC zum Klimawandel und zur Landnutzung unterscheidet sechs Arten von Barrieren, die Minderungsmaßnahmen im Agrarsektor behindern: Wirtschaftliche Barrieren bedeuten, dass Marktstrukturen und Marktteilnehmer durch z. B. niedrige Weltmarktpreise, etablierte Infrastruktur, Mangel an Absatzmärkten für klimafreundliche Lebensmittel usw. gegen mehr ehrgeizigen Klimaschutz in der Landwirtschaft arbeiten. Politische/gesetzliche Barrieren umfassen bestehende Gesetze und Vorschriften, finanzielle Anreize oder Ressourcen und die Ausgestaltung von Anreizen auf nationaler, regionaler und internationaler Ebene, von denen einige ehrgeizigen Klimamaßnahmen in der Landwirtschaft entgegenwirken. Technische Barrieren beziehen sich auf fehlendes Wissen oder die mangelnde Verfügbarkeit geeigneter Technologien. Sozio-kulturelle Barrieren resultieren aus Verhaltens- und Lebensmustern oder den Werten, die unserer Ernährung und unserer Einstellung gegenüber Lebensmitteln zugrunde liegen. Institutionelle Barrieren aufgrund der Verteilung von Kompetenzen auf verschiedene Regierungsinstitutionen können Reformprozesse ebenfalls verkomplizieren. Biophysische oder umweltbedingte Barrieren umfassen Faktoren, die die

Nutzung fruchtbarer Flächen oder die Lebensmittelproduktion reduzieren, wie Versalzung, Temperaturanstieg oder extreme Wetterereignisse wie Überschwemmungen oder Dürren.

Eine Vielzahl verschiedener Barrieren behindert die Minderung von Emissionen im Agrarsektor. Diese Barrieren können danach unterschieden werden, auf welcher politischen Ebene zur Umsetzung von Maßnahmen ergriffen werden müssten, wobei die oben genannte Kategorisierung in verschiedenen Arten von Barrieren durch den IPCC berücksichtigt wird.

Auf der Betriebsebene führen u.a. wirtschaftliche Barrieren dazu, dass dem landwirtschaftlichen Betrieb keine spezifischen wirtschaftlichen Vorteile durch die Umsetzung von Minderungsmaßnahmen entstehen. Veränderungen können hohe Transaktionskosten für den Landwirt oder die Landwirtin bedeuten. Zusammen mit einem mangelnden Zugang zu Krediten oder anderen finanziellen Ressourcen und Unsicherheit hinsichtlich der langfristigen wirtschaftlichen Vorteile von Minderungsmaßnahmen kann die Anreizwirkung, Risiken einzugehen und bestehende Praktiken zu modifizieren, gering sein. Weitere Barrieren auf Betriebsebene sind unsicherer Landbesitz, mangelnde Beratung oder Information und die Notwendigkeit, persönliche Einstellungen, Traditionen und Praktiken zu ändern.

Nationale Prioritäten und bestehende Gesetze können Aktivitäten zur Minderung von Emissionen unterstützen oder behindern. Wenn vor allem potenziell negative Auswirkungen auf die Produktion und der Widerspruch zu wirtschaftlichen Zielen zur Steigerung des landwirtschaftlichen Outputs im Vordergrund stehen, steht dies Minderungsmaßnahmen entgegen. Aber selbst wenn nationale Ziele die Minderung von Emissionen vorschreiben, können bestehende Gesetze zur Förderung der Produktion, wie Subventionen für Inputs oder Steuerbefreiungen, Klimaschutzmaßnahmen behindern.

Zu den Barrieren für die Minderung auf internationaler Ebene gehört das Risiko der Verlagerung von Emissionen in andere Länder. Außerdem erschweren lange Lieferketten, insbesondere im Kontext von Entwaldung, an denen viele Akteure beteiligt sind, die Minderung von Emissionen entlang der gesamten Produktion. Asymmetrische Handelsstrukturen und Machtungleichgewichte verstärken die wirtschaftliche Vulnerabilität von Landwirt:innen und können die Einführung neuer Anbaupraktiken erschweren.

Schließlich stehen Verbraucherpräferenzen, die auf sozialen und kulturellen Gewohnheiten beruhen, dem Übergang zu nachhaltigen Ernährungsweisen und der Reduzierung von Lebensmittelverschwendung entgegen. Dazu gehören Ernährungsgewohnheiten, die einen hohen Fleischkonsum mit sich bringen oder Präferenzen für Lebensmittel mit bestimmter Form und Erscheinungsbild.

Überwindung von Barrieren zur THG-Minderung in den ausgewählten Ländern

Die Barrieren für die Minderung im Agrarsektor zeigen weltweit ähnliche Muster, und dennoch variieren die nationalen, regionalen oder lokalen Herausforderungen, Bedürfnisse und Prioritäten. Gemeinsame Herausforderungen auf Betriebsebene umfassen das mangelnde Wissen der Landwirte über Minderungsoptionen und den begrenzten Zugang zu Vorfinanzierungen. Die Verbreitung von Wissen über nachhaltige Praktiken neben zugänglichen finanziellen Anreizen kann dazu beitragen, solche Barrieren zu überwinden. Die Einbeziehung lokaler Interessengruppen und die Wertschätzung indigenen Wissens durch partizipative Ansätze können die Annahme nachhaltiger Praktiken weiter fördern. Das Lernen von Landwirt zu Landwirt hebt sich als entscheidender Weg hervor, um kontextspezifische nachhaltige Produktionspraktiken umzusetzen.

In vielen der analysierten Länder sind gesetzliche Vorgaben für den Agrarsektor, einschließlich Produktionszielen und dem Streben nach Selbstversorgung, derzeit von Klimazielen entkoppelt und werden oft von verschiedenen Ministerien verwaltet. Die Integration von Klimazielen in landwirtschaftliche Produktionspläne könnte Minderungsmaßnahmen stärken und die Resilienz des Sektors gegenüber negativen Klimaauswirkungen stärken. Die Beteiligung vielfältiger Interessengruppen, einschließlich Landwirtinnen und Landwirten, Herstellern, Einzelhändlern, sowie lokalen und nationalen Regierungen, kann robuste nationale Rahmenbedingungen für die Reduzierung von Emissionen im gesamten Ernährungssystem schaffen.

Branchenweite Emissionsvorschriften sind notwendig, um zu verhindern, dass sich die Produktion durch Effizienzgewinne insbesondere in der Tierhaltung, ausweitet. Eine verbesserte Koordination zwischen den Ministerien für Gesundheit, Landwirtschaft, Wasser und Umwelt ist entscheidend, um Politiken zur Förderung nachhaltiger Ernährung zu harmonisieren. Die Ausrichtung landwirtschaftlicher Subventionen auf Nachhaltigkeit und Qualität anstelle von Output ist entscheidend. Finanzielle Anreize für nachhaltige Praktiken sollten strengen Vorschriften unterliegen, um eine ungewollte Produktionserweiterung oder die Verlagerung von Emissionen zu vermeiden. Wirtschaftliche Instrumente (z. B. Steuern, Subventionen) könnten die ökologischen Auswirkungen von Produkten widerspiegeln, um die Nachfrage nach ressourcenintensiven Artikeln wie Fleisch zu reduzieren. Im öffentlichen Bereich können Vorgaben für die Beschaffung dazu beitragen, Ernährung nachhaltiger zu gestalten. Reformen von Landbesitz und -Nutzung können dazu beitragen, Entwaldung zu reduzieren und die landwirtschaftliche Bewirtschaftung nachhaltiger zu gestalten.

Um internationale Barrieren für nachhaltige Ernährungssysteme zu überwinden, ist es unerlässlich, dass multilaterale Initiativen und globale Gipfeltreffen einen umfassenden Rahmen durch Ziele, Standards und fortlaufende Diskussionen schaffen. Insbesondere Veranstaltungen wie das UN-Food Systems Gipfeltreffen und die Konferenzen der Vertragsparteien (COPs) unter dem Übereinkommen über die biologische Vielfalt (CBD) und der UNFCCC dienen als Plattformen zum Austausch über gemeinsame, globale Bemühungen. Landwirtschaftspolitiken und Handelsstrukturen müssen auch auf internationaler Ebene reformiert werden, um nachhaltigere landwirtschaftliche Praktiken zu fördern, einschließlich gerechterer Preise für Landwirtinnen und Landwirte, der Bekämpfung negativer Auswirkungen von Nahrungsmittelkartellen und Finanzspekulationen, die vulnerable Bevölkerungen in einkommensschwachen Nationen betreffen, und der Umsetzung von Marktregulierungen und Fair-Trade-Gesetzen, die Risiken gerechter zwischen Produzenten und Einzelhändlern verteilen. Darüber hinaus müssen alle Interessensgruppen entlang der Lieferkette kontextspezifisch einbezogen werden, um zu verhindern, dass sich die landwirtschaftliche Produktion weiter ausdehnt und Entwaldung mit sich bringt. Um Entwaldung zu bekämpfen, sind internationale Vorschriften erforderlich. Gleichzeitig können multilaterale öffentlich-private Partnerschaften Synergien zwischen öffentlichen Maßnahmen und privaten Initiativen zur Bekämpfung von Entwaldung schaffen.

Auf Verbraucherebene ist gleichzeitig eine umfassendere gesellschaftliche Transformation erforderlich. Bildungskampagnen, Dialoge und Maßnahmen, um nachhaltige Lebensmittel erschwinglich zu machen, können dazu beitragen, die sozio-kulturellen und wirtschaftlichen Barrieren zu überwinden, die die Akzeptanz nachhaltiger Ernährungsweisen behindern.

Es ist jetzt wichtiger denn je, Strategien zu verfolgen, um die Ernährungssicherheit auf globaler und nationaler Ebene mit dem Kampf gegen den Klimawandel und den Verlust der Artenvielfalt in Einklang zu bringen, um in Zukunft ein nachhaltigeres Ernährungssystem für alle zu erreichen. Die Mittel zur Minderung von Emissionen aus der Landwirtschaft und gleichzeitigen Förderung der Ernährungssicherheit sind vorhanden. Um eine nachhaltige Transformation unseres Ernährungssystems zu erreichen, müssen wir unsere Herangehensweise und unsere Einstellung zur Landwirtschaft überdenken, anstatt uns nur auf technische Lösungen zu konzentrieren. Dazu braucht es das Engagement von Regierungen, Unternehmen, Produzenten und Verbraucherinnen und Verbrauchern, unterstützt von einer auf internationaler Ebene festgelegten 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 quarter 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 (Shukla et al. 2019, 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 based on plants 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 from 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 the project "Ambitious GHG Reduction in Agriculture: Analysis of Sustainable Potentials in Selected Priority Countries" (FKZ 3720 41 504 0), the contractors supported UBA in administrative-logistical tasks related to the coordination of the EU thematic group on land use IG AFOLU during the German Council Presidency in the second half of 2020 and prepared background papers on the land use-related processes under the UNFCCC.[8] Moreover, the contractors in this project analysed barriers to ambitious climate protection in agriculture and approaches to overcome them (Siemons et al. 2023a). Thirdly, the project looked into the agricultural sector of ten selected countries and identified potentials for more ambitious climate protection in these countries.[9]

This final report summarises mitigation measures in the agricultural sector (chapter 2), potentials for ambitious climate action in agriculture in ten selected countries including a description of the methodological approach (section 3) and findings on barriers to ambitious

[8] The papers are available for download at https://www.umweltbundesamt.de/en/topics/climate-energy/ambitious-greenhouse-gas-mitigation-in-agriculture.

[9] See https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-argentina; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-australia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-brazil; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-china; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-egypt; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-indonesia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-new-zealand; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-south-africa; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-uk; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-usa.

climate protection in agriculture (section 4). Section 5 presents some overarching conclusions from the findings across all countries.

2 Mitigation measures in the agricultural sector and barriers for implementation[10]

In work package 2 of the present research project, 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 were identified based on a literature review. The identified barriers were clustered and recommendations were developed to overcome them.

For the agricultural sector, a technical mitigation potential of 11.2 $GtCO_2e$/year (middle value of range) on the supply side from carbon sequestration (e.g. agroforestry) and global measures to reduce methane and nitrous oxide emissions from enteric fermentation, rice cultivation, etc. was identified by the IPCC (Nabuurs et al. 2022). Most of this potential is derived from the enhanced carbon sinks instead of emission reductions from agricultural production. On the other hand, 4.2 $GtCO_2e$/year of technical mitigation potential was identified on the demand side by 2050 – mainly from shifting to sustainable healthy diets. To achieve this mitigation potential, demand-side measures to address dietary habits would need to be integrated in an overall strategy to reduce production volumes/livestock numbers (e.g. limiting livestock numbers per area). The economic mitigation potential is estimated to be approx. 4.1 $GtCO_2e$/year (middle value of range) from agriculture (incl. carbon sequestration) and approx. 2.2 $GtCO_2e$/year on the demand side by 2050 at carbon prices up to 100 USD tCO_2 (ibid).

Mitigation options considered include supply-side and demand-side activities. 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 are not on-farm measures are briefly outlined. Measures to directly reduce livestock numbers on the supply side were not considered in the analysis because these would need to be integrated with measures on the demand side to avoid leakage effects instead of being implemented as separate, stand-alone measures and currently lack political support. However, measures for reducing livestock numbers or changing dietary patterns are highlighted as additional mitigation options. (see section 3.3.2 for a description of our approach for selecting prioritised mitigation measures).

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. As adaptation to climate change is of paramount importance specifically in agriculture, the proposed measures and instruments should at least not conflict with adaptation goals and ideally have synergies with them. However, suitable approaches for the development of food systems need to be context-specific as agricultural systems and barriers obstructing the implementation of mitigation approaches are highly diverse and specific to local circumstances.

WP2 resulted in a policy paper that summarises the main barriers to ambitious climate protection in the agricultural sector and recommendations for overcoming them. The policy paper provides a brief overview of selected mitigation options in the agricultural sector and

[10] 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.

highlights barriers identified in the literature for each of these options (Siemons et al. 2023b). A summary of the paper is included in this report.[11]

2.1 Mitigation measures in the agricultural sector

2.1.1 Supply-side measures

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

- **Changes in the cultivation system**: 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). In smallholder contexts in the global South, sustainable agricultural practices 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 und 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) **changing the cropping area** to the extent that 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; (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 (Oberč und Arroyo Schnell 2020); (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, approx. 50% of the nitrogen applied to agricultural land is not absorbed by crops. 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 (Shukla et al. 2019, 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.

[11] The full paper is available at https://www.umweltbundesamt.de/en/publikationen/barriers-to-mitigating-emissions-from-agriculture.

- **Improved management of livestock manure**: Overall, manure from livestock accounts for roughly 25% of direct agricultural GHG emissions (Dickie et al.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 animal 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 (Dickie et al.2014). **Digesters** can convert manure into methane for energy use. However, this would only result in a net emissions decrease if the manure would otherwise be stored in wet form and methane leakage rates were 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. **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). However, the only way of reducing emissions from manure left on pasture sufficiently is by **reducing livestock numbers** and thus, the overall volume of deposited manure.

- **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** (Gerber et al. 2013). 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). 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. Hence, these measures would only result in a decrease of absolute emissions if **animal numbers were reduced** in conjunction, which would be the most effective way to reduce emissions from livestock, but faces various economic and social barriers (FAO and New Zealand Agricultural Greenhouse Gas Research Centre 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 (primary and secondary cereals, grain legumes, temporary fodders, and to a lesser extent oilseeds, vegetables and root crops) need to be alternated. In nutrient-deficient systems, **additional external fertiliser** can be used to increase carbon stored in soils. **In grasslands, the optimal density of stocking and grazing** can increase soil carbon sequestration (Paustian et al. 2016). Additionally, the addition of exogenous carbon inputs such as composts or biochar is being discussed as a measure to increase soil carbon stocks. The mitigation effect of exogenous carbon inputs, however, needs to be assessed in the context of a broader life-cycle assessment. Increasing the carbon stored in soils implies multiple other environmental and social benefits. By emphasising the adaptation and other environmental benefits of measures to enhance soil carbon, mitigation results could be realised as co-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 2021b). **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 (Bouman et al. 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 management practices to reduce GHG emissions from rice cultivation include **improved rice straw management, improved fertiliser management, changes in planting methods and improving rice varieties**.
- **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. 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).

2.1.2 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. Demand-side measures to change production and consumption patterns can not only reduce and avoid emissions, but also reduce pressure from land use and allow for restoration of natural ecosystems and forest due to less land needed for agricultural use (Fuentes Hutfilter et al. 2020). Three key approaches for tackling emissions from agriculture on the demand side include:

- **Reducing food waste and losses**: FAO (2019) 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 2019). The loss of edible food and 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 and 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 (Shukla et al 2019; FAO 2019; HLPE 2014; Poore and 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 strengthen food producers' position in the supply chain, and improving packaging during the supply chain (Shukla et al. 2019, p. 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 on buying and using food at home (Rosenzweig et al. 2020). Reducing food loss and waste also contributes to food security.

- **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 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 developed countries as well as adopting a plant-rich diet**. **Excluding animal products** from the diet can make a huge difference, whereas shifting from beef plays a superordinate 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 et al. (2020), could help to reduce health *and* climate change costs by 2030, as their hidden costs are lower than those of current food consumption patterns. 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 et al. 2020). 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 a strong tool to ensure food security for a global population (Wunder et al. 2021).

- **Avoiding deforestation to create arable land and grassland**: Eliminating net deforestation in the next decade is a key component of emissions pathways consistent with 1.5°C. 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). 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. Avoiding deforestation emissions from agricultural expansion can be broadly addressed in two ways; (1) **measures that directly target deforestation and preserve forested areas**, including improved governance for the legal protection of forested areas and reforms to private sector supply chains to reduce illegal deforestation, and (2) **measures that reduce the demand for new agricultural land and its expansion into forests**, e.g. by changing existing farming practices that sustainably intensify production, restoring degraded farmland to reduce the pressure for agricultural expansion or employing conversation agriculture practices to replenish lost nutrients.

3 Potential for ambitious climate action in agriculture in 10 selected countries

3.1 Approach

National plans and long-term strategies for reaching climate targets do not generally lay out detailed plans for reducing (and avoiding) emissions from agriculture. We examined the national circumstances and current mitigation plans for 10 individual countries with the goal of identifying additional mitigation potential. Based on the analysis of available mitigation measures in the agricultural sector and barriers to implementing these measures (section 2 and 4), we further identified potential barriers to meeting that mitigation potential and possible approaches to addressing those barriers.

In this report, we also describe the **methods (including literature estimates) used to evaluate the mitigation potential** of selected measures in each of the countries and the challenges encountered implementing those methods. The 10 countries studied are Australia, Argentina, Brazil, China, Egypt, Indonesia, New Zealand, South Africa, the United Kingdom, and the United States. Individual reports for each country are published separately.[12]

The analysis for each country encompasses four major components, each of which are described in more detail below.

1. Analysis of the current agricultural policy landscape and major emissions sources.
2. Identification of three priority mitigation options and their mitigation potential.
3. Identification of barriers to achieving mitigation potential and
4. Recommendations for enhancing mitigation action in the agricultural sector.

The analysis for each country builds on the analysis of barriers presented in chapter 2 above and identifies those aspects that are most relevant to the specific country.

3.2 Country specific circumstances and current policy landscape

3.2.1 Methods for assessing the status of the agriculture sector

Measures to reduce and avoid greenhouse gas emissions in AFOLU are diverse and can target both the supply and demand of agricultural goods (such as grain, meat and dairy products, timber, etc.). The relevance and potential of individual measures varies both regionally and nationally. These depend, among other things, on the key products from the agricultural sector, the degree of intensification of production systems, agri-climatic conditions and adaptation needs, cultural and socio-economic conditions, and the nature of agricultural trade. Particularly, any mitigation measure must be considered in the context of national development priorities in countries where food security is not ensured for the whole population. Recommendations for

[12] See https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-argentina; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-australia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-brazil; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-china; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-egypt; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-indonesia; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-new-zealand; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-south-africa; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-uk; https://www.umweltbundesamt.de/publikationen/mitigating-agricultural-greenhouse-gas-emissions-in-the-usa.

effective mitigation measures must therefore be appropriate and tailored to national circumstances.

In order to do so, a qualitative analysis of the characteristics and circumstances of the agricultural sector in each of the selected countries was conducted based on existing emission profiles for agricultural activities, the socio-economic background, trade and employment data, current national climate policies, vulnerability of the agricultural sector to the impacts of global warming and food consumption and waste trends. These country profiles informed the quantitative and qualitative analysis of GHG mitigation potential for selected key measures to ensure the relevance and integrity of the resulting recommendations. The options identified are analysed in terms of their contribution to national and global food security goals, climate resilience and adaptive capacity, and the barriers and approaches to implementing the measures identified in WP 2. All country-specific analyses follow a common methodological framework to ensure both comparability of results and consistency of conclusions and recommendations for action.

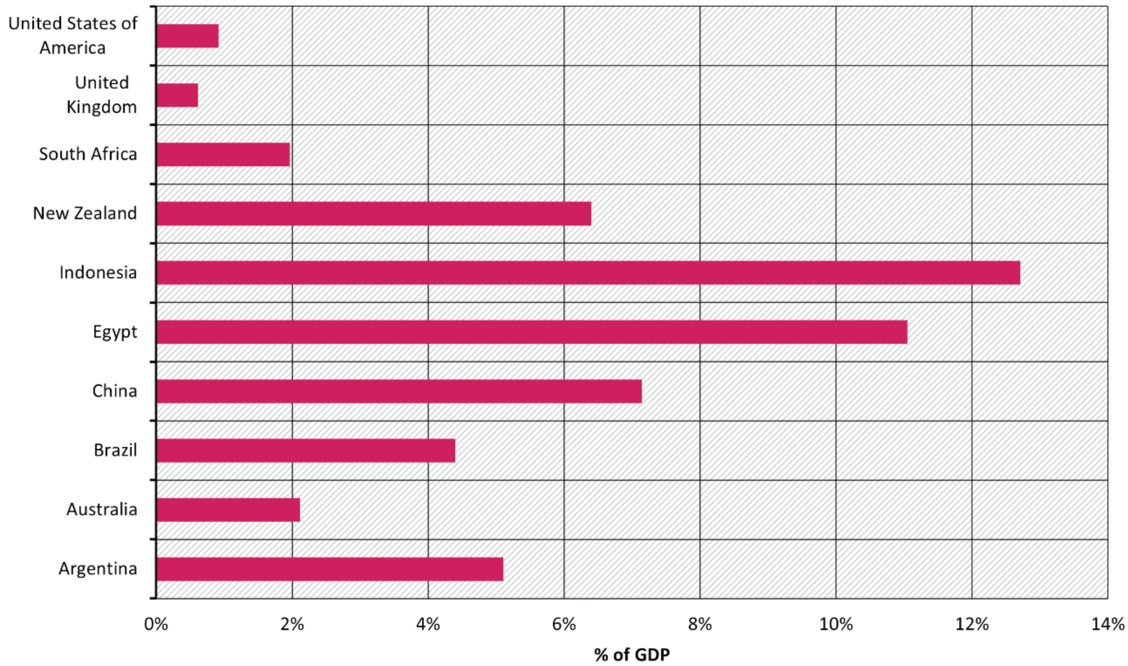
To examine these elements, sources of information analysed for the selected countries include: data from FAOStat, emissions data and reports submitted by countries to the UNFCCC, national government reports, policies from the NewClimate-developed database on climate-related actions (climatepolicydatabase.org), the Climate Action Tracker (CAT), reports on climate vulnerability and climate-smart agriculture from the World Bank and CGIAR, as well as available scientific literature.

The results of the work explicitly represent scientific research results and not policy advice for the countries studied.

3.2.2 Key insights on status of agriculture sector across the ten focus countries

The role of agriculture in the economy varies substantially across the 10 countries studied. As a share of contribution to GDP, agriculture, fisheries and forests vary from as low as 0.6% in the UK, to as high as over 13% in Indonesia (Figure 1). Most of the countries studied view the agricultural sector as critical to foreign export earnings and in some countries, agriculture made up over half of export revenues (e.g. Argentina).

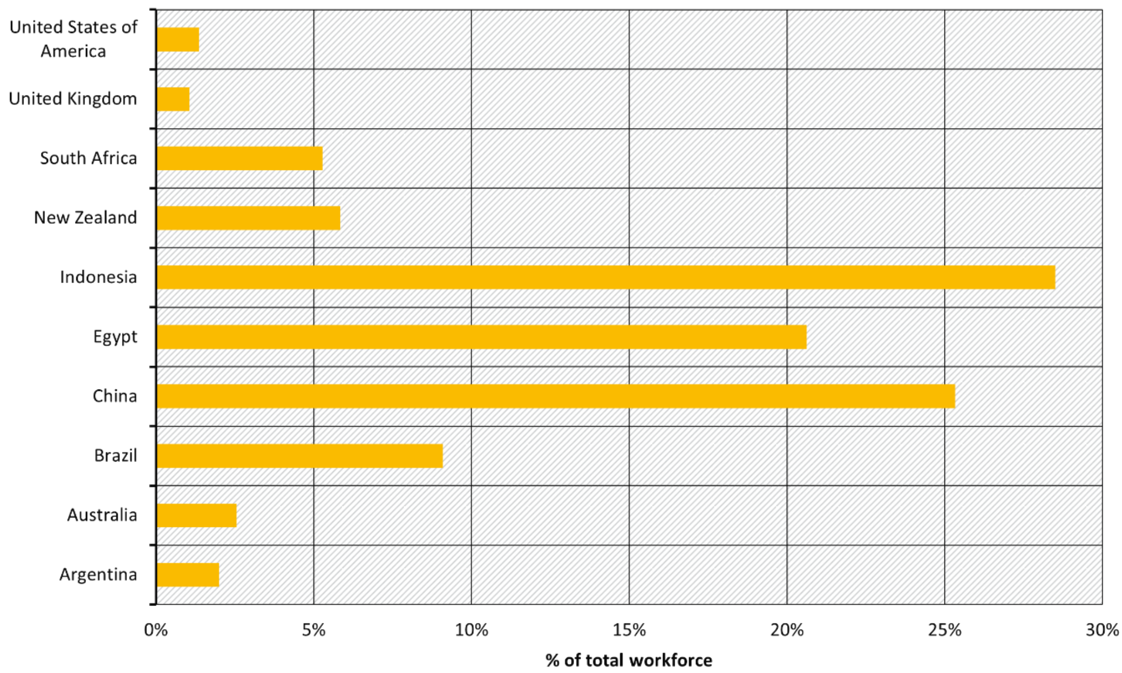
Figure 1: Agriculture, fisheries, and forestry's contribution to GDP (2019)



Source: World Bank (2022) data for all countries except New Zealand due to lack of data. Value for New Zealand was taken from OECD (2021).

The extent of agricultural employment also considerably varies across the countries (Figure 2). Countries such as the US, Australia, Argentina, etc. have low employment rates due to the high degree of mechanisation, while the agricultural sector makes up about a quarter of employment in Indonesia, Egypt, and China. The nature of the farming can be very different; in some countries smallholder farming practices are dominant while in other countries there are a few, large farms. In general, the agricultural sector has become increasingly consolidated since the 1990s, with large-scale operations making up an ever-greater share of agricultural production and land. Although mitigation options may be similar, the barriers and challenges to implementation can be quite different across farm sizes. The agricultural sector plays an important role in rural development and poverty alleviation, especially for smallholder farmers in developing countries that aim to transition from subsistence to commercial farming.

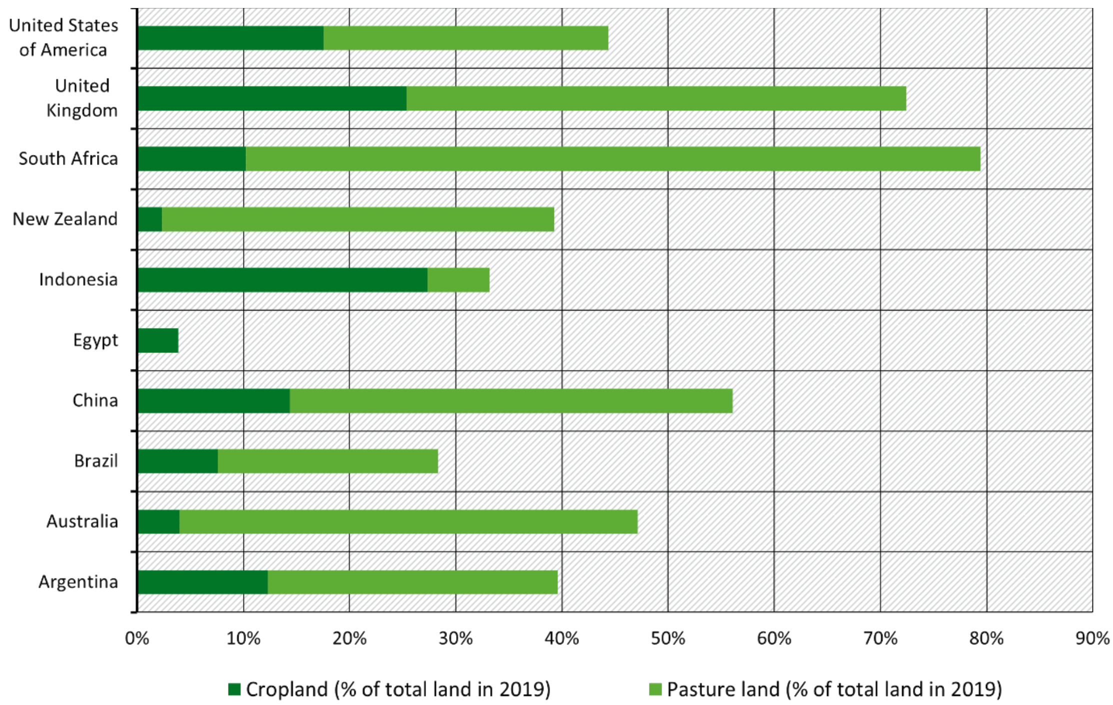
Figure 2: Agricultural employment as a share of total workforce (2019)



Source: World Bank (2021) data for all countries except Argentina due to data discrepancy. Value for Argentina was taken from ILO (2021).

Most of the countries studied have a significant portion of their land dedicated to the agricultural sector (Figure 3). On the low end is Egypt, who has a miniscule portion of arable land concentrated around the Nile delta as well as no designated pastureland, as livestock are either kept in stables or raised on the same land used to grow crops. South Africa's agricultural land makes up almost 80% of the country's total area, but only a small portion is considered arable and of high agricultural potential. Pasture land dominates the agricultural land use in many countries since livestock often graze on marginal land where other crops cannot be grown.

Figure 3: Agricultural land as a share of total country area (2019)



Source: FAO (2022b) data for all countries. Data includes "Cropland" and "Land under permanent meadows and pastures".

The agricultural sector and water security are highly interlinked, especially in water-scarce countries such as South Africa, Australia and Egypt. The agricultural sector is responsible for most water use in these countries, which has led to some controversy as to how the resources are distributed.

3.2.2.1 Key emission sources and entry points for mitigation actions

A first step in identifying priority mitigation options for each country was to identify the dominant emissions sources, which also helped us understand the similarities and differences in the agricultural sector across the countries. It is informative to examine the sources of emissions both in absolute terms (Figure 4; Figure 6) and as a share of the total (Figure 5; Figure 7) agricultural emissions.

Key emission sources vary somewhat by country (compare the above-mentioned figures), but there are some predominant patterns. Enteric fermentation, manure management, manure deposited on agricultural land and on-farm energy use are the most substantial contributors to agricultural emissions across all countries, with enteric fermentation commonly being the largest source.

The livestock sector, specifically cattle, dominates the agricultural emissions profiles across all the countries studied. In some of the analysed countries, emissions from other livestock can significantly contribute to agricultural GHG emissions. For instance, Egypt has a considerable buffalo population that is responsible for almost half of the country's enteric fermentation emissions. New Zealand's large sheep population has a sizable contribution to total enteric fermentation emissions. In China, pigs are the dominating livestock.

High-productivity, intensive systems have high-yielding cattle that are either concentrated in confinement systems or grazing on high quality pastures with supplemented feed (i.e. grain-finishing). The productivity of these systems are high and enteric fermentation emission intensities are rather low per tonne of milk or meat production, but specific emission factors per head are generally equivalent to or higher than in low-productivity systems (for dairy cattle in particular). In addition, CH_4 emissions from manure management can be very high in intensive production systems when large livestock farms do not store and manage their manure sufficiently, e.g. by covering the slurry or/and using anaerobic digestion for manure. Additionally, there can be high N_2O emissions from spreading of manure to the soil, if farms do not have sufficiently large agricultural areas for crops to take up collected manure. There are also numerous animal welfare concerns in industrialised livestock systems.

Low-productivity, extensive systems are less efficient and more emission-intensive in terms of milk and meat production but can also have lower emission factors per head. The decomposition of manure under anaerobic conditions, during storage and treatment, produces CH_4. These conditions occur most readily when large numbers of animals are managed in confined systems, and where manure is stored in liquid form. When manure is deposited on pastures, it decomposes under more aerobic conditions with less CH_4 production. Therefore, CH_4 emission factors from manure left on pasture in extensive grassland systems are generally much lower than manure emissions managed from intensive animal production systems. On the other hand, N_2O emissions factors can be slightly higher for manure decomposed on pastures than for manure spreading on cropland or pastures. At the same time, emissions from manure left on pasture are very difficult to mitigate beyond reducing herd sizes (while animal head per area are usually not very high in extensive systems).

In countries in which rice is a staple food and extensively grown, rice emissions are a major contributor to total agricultural emissions (e.g. China, Indonesia, Egypt). Rice production commonly occurs under continuous flooding conditions, which results in significant CH_4 emissions from the anaerobic environment. Intermittent flooding or alternative wetting and drying rice cultivation systems are much less emissions-intensive (Livsey et al. 2019).

Emissions from crop production are predominantly derived from synthetic fertiliser use. Most of the countries analysed currently overapply fertiliser to their fields, resulting in significant nutrient losses and corresponding environmental pollution and emissions. In part, the overuse of fertiliser is driven by low fertiliser costs achieved through government subsidies.

Soil tillage without appropriate soil carbon management and lack of erosion prevention can reduce soil organic carbon in mineral soils on croplands, which can also be a significant source of emissions, while management methods that increase soil carbon are also beneficial for soil health, water and nutrient storage capacity.

In some cases, LULUCF emissions can completely overshadow agricultural emissions. Land-use change emissions are generally driven by deforestation for agricultural expansion, which includes the drainage and burning of peatlands in the case of Indonesia. Of the ten countries we examined, deforestation emissions are particularly relevant for Indonesia and Brazil, but also Argentina and the USA.

3.2.2.2 Policy frameworks in the agricultural sector

The governance structure and climate change policy framework of the agricultural sector is very different across countries. In some cases, the agricultural mitigation activities are implemented by the relevant environmental department or ministry, while other countries put the responsibility onto the agriculture (or agribusiness) ministry. Most of the countries do not include a sectoral target for the agricultural sector in their NDC. In general, many of the countries' current climate pledges are incompatible with a 1.5°C emissions pathway.

Several countries have developed a climate change sectoral plan for the agriculture sector. However, few of these plans reference the need to change production patterns or demand side patterns like diets. On the contrary, the plans usually highlight government objectives to increase agricultural production for food security and/or economic growth. Some countries do not include mitigation measures related to livestock, despite the livestock sector being the key emissions source (Argentina). Other countries rely on technological measures that are difficult to scale (Australia).

For countries in which deforestation is relevant, there generally are laws meant to protect native forests and delineate conservation areas, for instance, the Brazil New Forest Code or Argentina's Native Forest Law. However, deforestation is still occurring in protected areas under these laws due to a lack of enforcement, stemming from a lack of government funds and capacity.

The adoption of certain regenerative agricultural practices (e.g. low- or no-till, crop rotations, cover crops) has gained traction in some countries. Most of it has been an adaptation response to changing climactic conditions like increased drought frequency.

3.2.2.3 Demand-side and external factors

Demand-side and external factors have played a major part in shaping the agricultural landscape across all countries. Food waste, dietary habits, the COVID-19 pandemic, and climate change impacts all influence agricultural processes and related emissions. Many of the countries in this study are top consumers of animal products, although ruminant meat consumption has usually declined in favour of poultry. Argentina, Brazil, and South Africa have social and cultural traditions revolving around meat, and it makes up an important component of national identity. China is the largest pork producer and consumer in the world.

The Planetary Health Diet[13] is a set of guidelines that provides consumption recommendations that can nutritiously feed a growing population while being compatible with planetary boundaries. Recent meat consumption statistics indicate that most developed countries, such as Australia, the UK, and the US, are far beyond what is recommended to be healthy or sustainable and must reduce their total meat intake in the range of 70–80% (Four Paws 2023). But also milk consumption is in many countries far above the recommendation from the Planetary Health Diet.

Food waste volumes are considerable across all the countries studied. In developed countries, a significant extent of food is wasted at the household level and is linked to wasteful behaviour. Contrary to prior beliefs, on-farm food waste levels are higher in more affluent regions while household food waste plays a significant role across all income groups, including low-income countries (UNEP 2021; WWF 2021). Farmers in developed countries cite an inability to fund labourers, appearance standards, and market conditions as reasons behind harvest stage waste. In developing countries, food losses occur at the farm and processing level due to a lack of sufficient road infrastructure and cold chain technology, and poor harvesting techniques (ibid). Most countries have developed a food waste action plan; these plans focus on interventions at the end of the supply chain (i.e. household-level).

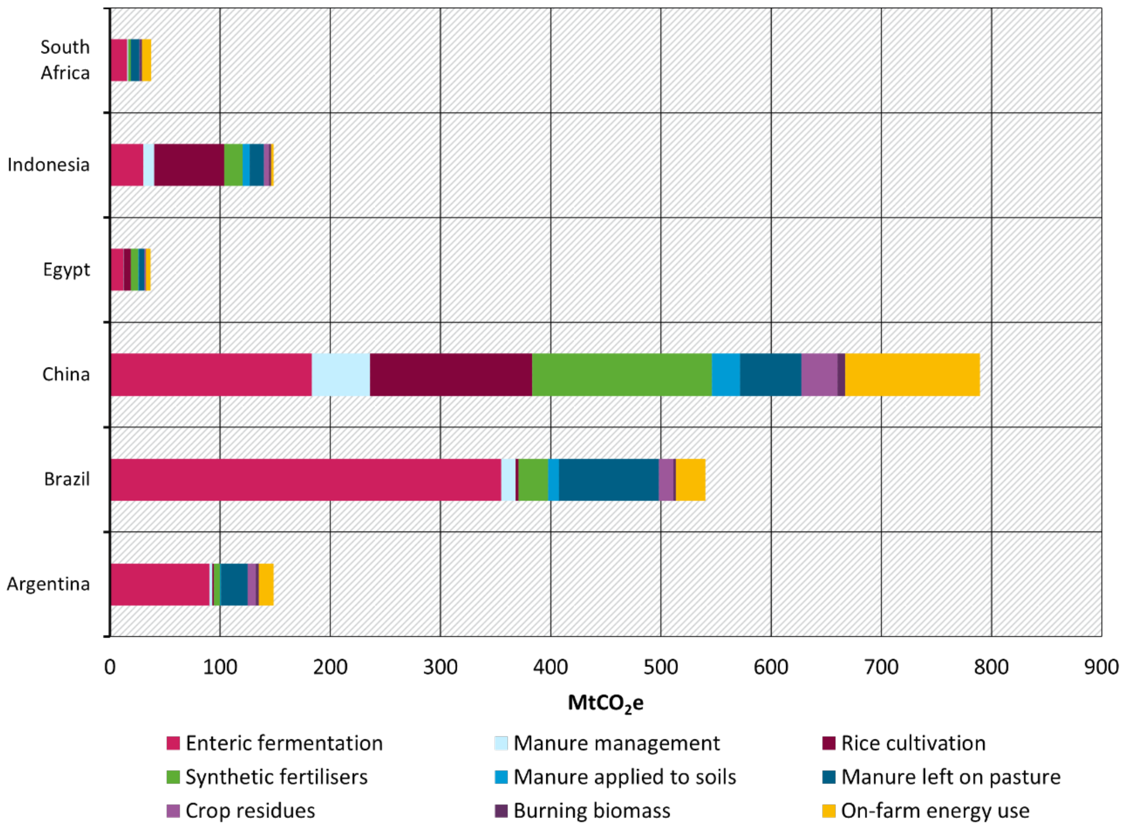
The COVID-19 pandemic significantly affected the agricultural sector. For instance, the US struggled to find on-farm labour, while farmers in Australia and South Africa grappled with revenue losses resulting from border restrictions or closures in local markets. Other external factors have also had a considerable impact on a country's agricultural sector, such as the uncertain macroeconomic environment in Argentina or wildfires in the US.

[13] https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you/

3.2.2.4 Vulnerability of the agricultural sector

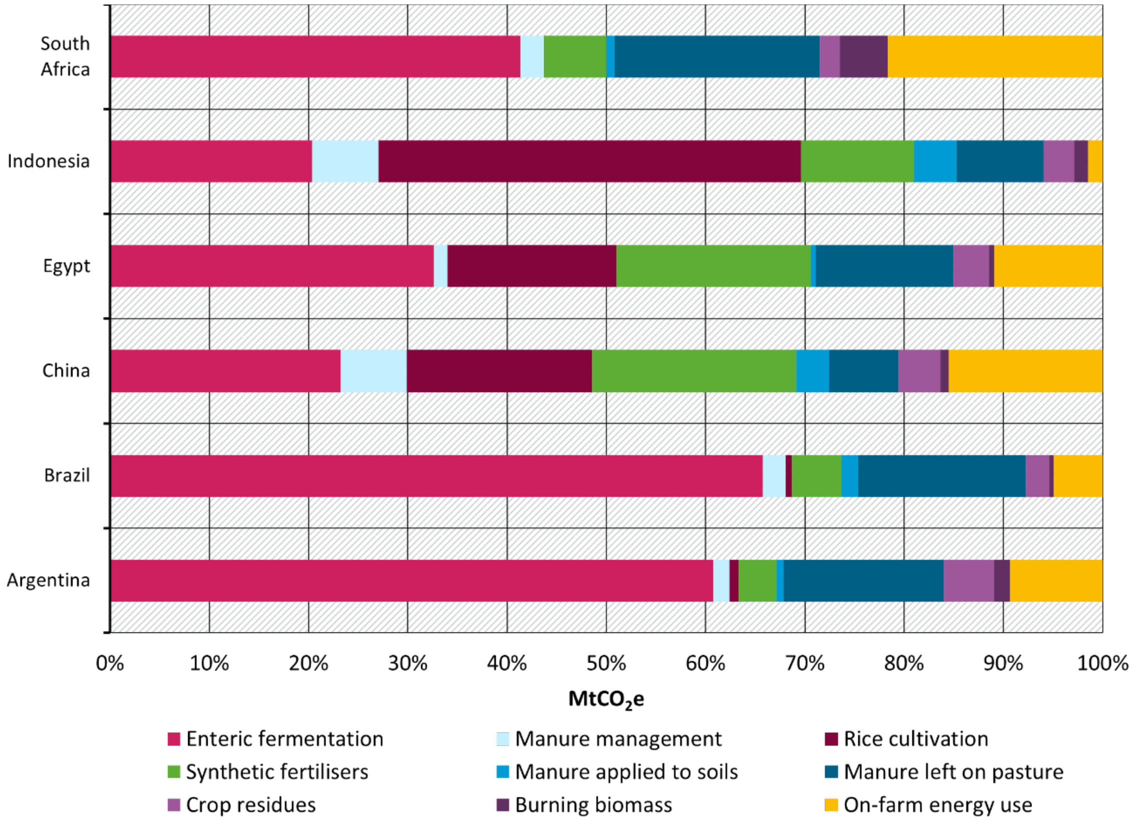
The agricultural sector is at high risk from climate change impacts, and all countries have already been affected in one way or another. Australia, South Africa, China and Argentina have all faced droughts in recent years, which affected yields and caused considerable livestock deaths. Drought episodes, other natural disasters (e.g. floods), and pest outbreaks are expected to become more frequent as global temperature increases. Crop production will likely be displaced across regions as general climactic conditions change. Livestock systems across countries are vulnerable to heat stress, affecting their productivity and profitability. Most countries have developed a national adaptation strategy, which cite regenerative agricultural practices as an important adaptation component.

Figure 4: Sources of agricultural emissions in the selected non-Annex I countries, presented as absolute values (2019)



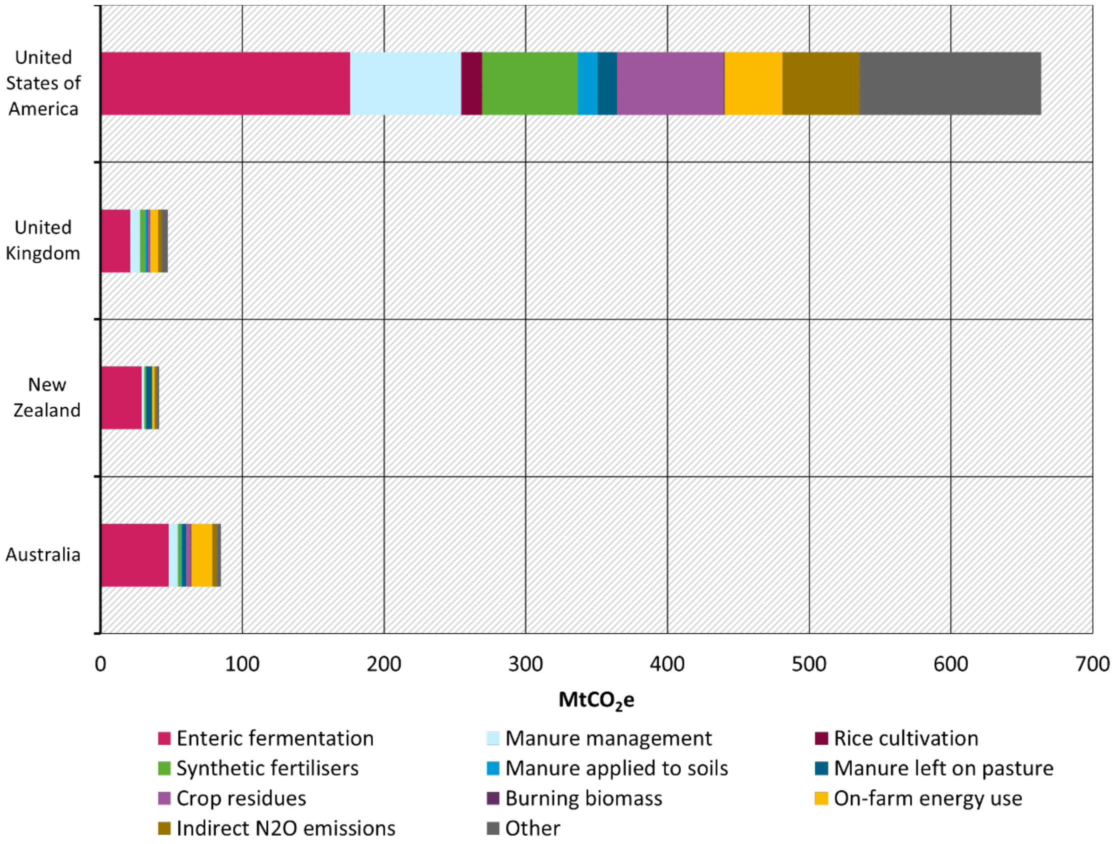
Source: FAO (2021a)

Figure 5: Sources of agricultural emissions in the selected non-Annex I countries, presented as a share of total agricultural emissions (2019)



Source: FAO (2021a)

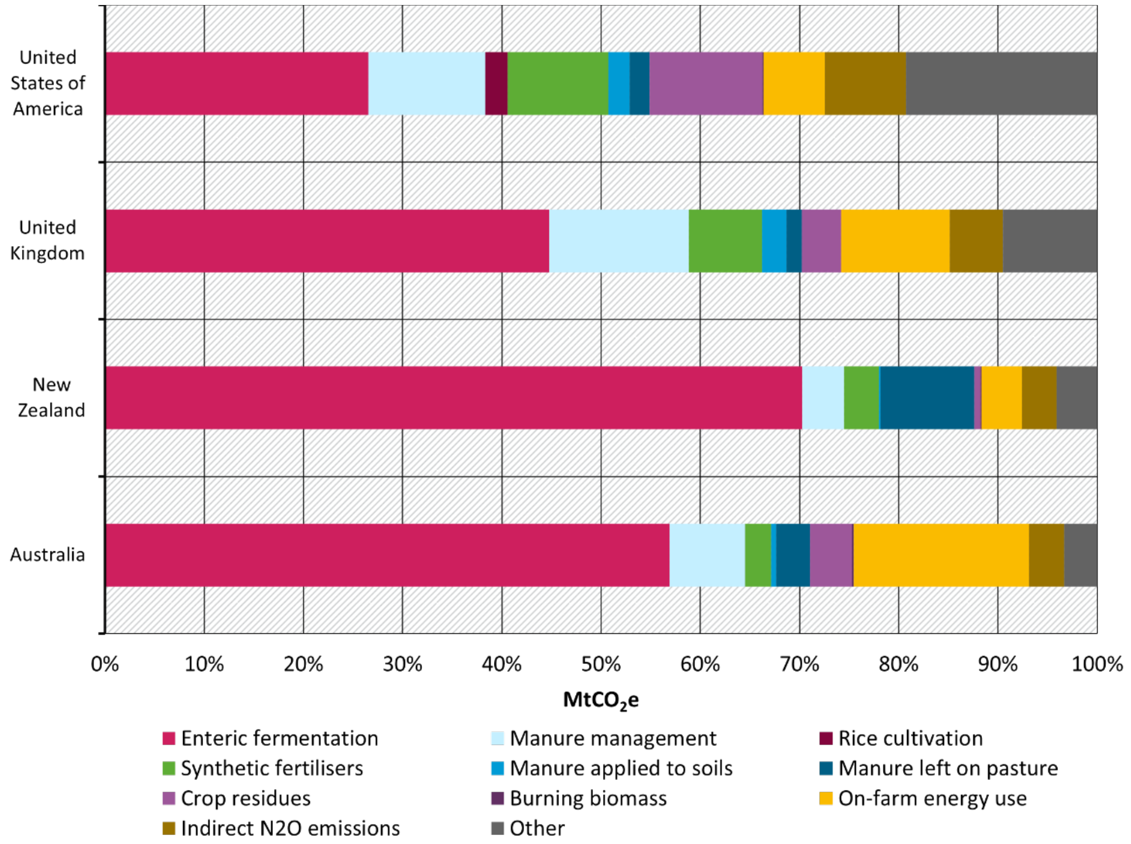
Figure 6: Sources of agricultural emissions in the selected Annex I countries, presented as absolute values (2019)



Source: Australian Government (2022a), New Zealand Ministry for the Environment (2022), UK Government (2022), United States of America (2022b)[14]

[14] While on-farm energy use is generally reported under energy sector emissions for national data, we include it as an agriculture-related emission source in this study because of its role in agricultural production (fuel use in harvesters, stable heating, grain drying etc.) and its relevance in several countries in terms of magnitude and mitigation potential. On-farm energy use was taken directly from the New Zealand and UK national GHG inventories. However, this data was not available for Australia and the U.S., and we opted to use FAO data. Due to the rather high uncertainties in FAO data, no mitigation measures for on-farm energy use are evaluated in the country papers. We refer to 2019 instead of 2020 data, which was the latest data available at the time of writing, due to COVID-related economic dynamics that affected national emissions in 2020.

Figure 7: Sources of agricultural emissions in the selected Annex I countries, presented as a share of total agricultural emissions (2019)



Source: Australian Government (2022a), New Zealand Ministry for the Environment (2022), UK Government (2022), United States of America (2022b)[10]

3.3 Quantification of mitigation potential in selected countries

3.3.1 General approach to quantification

Globally, mitigation potentials from reducing on-farm agriculture emissions are low compared to the carbon sequestration potential on agricultural land or in forests (Figure 8, Roe et al. 2021). Notably, demand-side measures of reducing food waste and changing diets have a higher overall mitigation potential compared to technical mitigation measures. In addition, there are positive indirect effects from dietary changes and reduction of food waste of preventing land use change and releasing land from agricultural production, as well as the reduced pressure on natural resources, although it is difficult to compare direct versus indirect emissions sources. However, to meet the Paris Agreement's 1.5°C warming limit, all avenues to reduce emissions will need to be pursued. As agricultural CH_4 and N_2O emissions are impossible to eliminate entirely, any emissions remaining will need to be counter-balanced in a net-zero, or net-negative, GHG emissions world. Reducing these emissions as far as possible, while still sustainably feeding the world's population, will reduce the need for carbon dioxide removal later in the century. It is therefore still worthwhile identifying what on-farm agricultural emissions can be minimised.

In section 2.1 of this report, we delineate the main mitigation options in the agricultural sector. Here we examine their mitigation potential and how that varies between countries. Three main elements contribute to where the most mitigation potential lies in a country: firstly, the main emission sources in the country, secondly, the footprint of existing agricultural systems in terms of emission intensities (tCO_2e/tonne of product) and thirdly, the sustainability of the production systems. Intensive production systems often require high inputs that cause emissions in other sectors (e.g. fertiliser production, on-farm energy use) or result in higher indirect emissions from increased fertiliser application and/or livestock grain feed production, including land use emissions from deforestation. It is equally important to consider the environmental, economic, and social co-benefits that arise from certain mitigation options.

Figure 8: Global mitigation potential of mitigation measures related to forests and other ecosystems, agriculture and demand side

Source: Roe et al. (2021)

Under this project, it is not feasible to quantify the full mitigation potential for each country since agricultural systems are extremely complex and multi-faceted. As such, we focus on three priority measures. The selection of these measures is determined based on the background research for that country and a set of prioritisation criteria, as outlined below (section 3.3.2).

To determine the appropriate quantification methods, the project team first evaluated the tools available for estimating mitigation potential in the agriculture sector. Many models were found to be too complex for this project and required detailed information that is not readily available at the national level (e.g. CCAFS Mitigation Options Tool, FAO EX-ACT). Therefore, the project team decided, as outlined in the proposal, to further develop in-house quantification tools and methods to estimate mitigation potential for key measures in each of the countries. In many cases, it became clear that it was not possible to derive our own estimate of mitigation potential, either due to the complexity of the systems or a lack of data. In such cases and where extensive information is available in national studies, we rely on existing literature to provide mitigation potential estimates. In all cases, we compare our results with those in the literature, if available.

The tools used are bottom-up, Excel-based, and modified for each specific measure. Estimates of mitigation potential are commonly based on a principle of modifications to an existing practice over an extended period of time. We used an approach based on activity and emissions intensity, where either changes in activity (e.g. tonnes of cattle meat produced) or emission intensity (e.g. tonnes of CO_2e per tonnes of cattle meat produced, tCO_2e/hectare of grassland) result in changes to emissions compared to 2019 levels or a baseline scenario. Where possible, we use a baseline projection that is based on a continuation of trends in national historic emissions or activities to outline the relative impacts of productivity changes and intensity improvements. Detailed methods for the relevant mitigation options, in addition to the limitations for quantifying certain measures, are described in section 3.3.3.

3.3.2 Selection of priority mitigation options

For each country, three priority mitigation options were identified for further analysis and quantification. First, a list of possible mitigation actions was identified based on research presented in chapter 2 (Table 1). The following questions were then used to guide the selection of measure for each country:

- ► Relevance to national circumstances
  - *What cropping and livestock systems are predominant in the selected country? What mitigation options are being explored by the government?*
  - We prioritised options that fit with the outlined use cases.
  - We highly considered options that have been outlined in national sectoral strategies for emissions reductions.
  - We also highly considered options that have significant environment, social, and economic co-benefits.
- ► Mitigation potential
  - *What are the largest sources of agriculture emissions?*
  - We prioritised options that would reduce emissions from sources where they are currently highest.
- ► Technological feasibility
  - *Is the option technologically possible, or is it experimental?*
  - We prioritised options that had a greater evidence base of successful emission reductions.

- Political feasibility
  - Is the option politically feasible or are there expressed developments that make the implementation of a measure unlikely?
  - We prioritised options that were referenced in policy documents and aligned with high level policy goals.

Measures to directly reduce livestock numbers on the supply side were not considered in the quantification analysis. Measures to achieve changes on the demand side of animal products also need to be integrated with measures on the demand side to avoid that an unchanged demand is fulfilled with an increase of imports (i.e. leakage). Measures on the demand or supply side to reduce animal numbers were not quantified, because political feasibility was one of the selection criteria and these measures currently lack political support in the analysed countries. However, given their importance for reducing emissions from agriculture, measures for reducing livestock numbers or changing dietary patterns are highlighted as additional mitigation options, particularly in countries where livestock numbers exceed recommended numbers and there is limited potential for efficiency gains.

The selected mitigation options are outlined for each country in Table 2 and the reasoning behind this selection is justified in each country dossier. Additional mitigation options with high mitigation potential or likelihood of adoption are highlighted in the text of the country dossiers and, where possible, mitigation potentials are provided based on existing literature.

Table 1: Mitigation options considered for the analysis

Agriculture Sub-sector	Emissions source	Mitigation option
Livestock	Enteric fermentation, manure management, grassland	Feed optimisation
		Health monitoring and disease prevention
		Breeding optimisation
		Manure management (incl. anaerobic digesters)
		Grazing land management or restoration
Cropland	Rice cultivation	Improved straw management
		Changes in flooding pattern (e.g. shifting from continuous to intermittent flooding)
		Sustainable intensification practices (incl. rice variety, fertilisation and irrigation management)
	Cropland & managed soil emissions	Low/no-tillage
		Cover crops
		Crop rotation
		Reduced synthetic fertiliser use and/or improved nutrient management
		Agroforestry

Agriculture Sub-sector	Emissions source	Mitigation option
		Integrated crop-livestock systems
	Biomass burning	Crop residue burning
		Grassland or peatlands burning
Land	Land use change	Silvopastoralism
		Preventing deforestation
Food system	- *(indirect impact on emissions)*	Shift in dietary preferences
		Reducing food loss and waste

Source: Authors' own compilation

Table 2: Mitigation options selected for analysis in each country

Country	Mitigation Option 1	Mitigation Option 2	Mitigation Option 3
Argentina	Silvopastoralism	Livestock emissions intensity reduction – disease prevention	Livestock emissions intensity reduction – feed optimisation
Australia	Grazing management and improved pastures	Silvopastoralism	Livestock emissions intensity reduction
Brazil	Preventing deforestation due to agricultural expansion	Restoration of degraded pastures	Improved nutrient management
China	Improved nutrient management	Improved rice cultivation practices	Improved manure management
Egypt	Improved nutrient management	Improved rice cultivation practices	Decarbonising on-farm energy use
Indonesia	Rice cultivation	Livestock emissions intensity reduction	Improve palm oil yield gaps to prevent future land expansion
New Zealand	Rewetting of organic soils	Reduced nitrogen fertilisation on pastures	Silvopastoralism
South Africa	Restoration of degraded pastures	No-till cropping systems	Livestock emissions intensity reduction
United Kingdom	Improved nutrient management	Cover crops (plants with improved nitrogen use efficiency)	Improved animal health
USA	Grazing land management	Improved nutrient management	Improved manure management

Source: Authors' own compilation

3.3.3 Methods for estimating mitigation potential through specific options

Where feasible and where comprehensive national studies are lacking, we provide our own quantification for each priority mitigation option in the ten countries. The general methods, along with country-specific information, are described in this section. For all quantitative estimates, we also performed a sense check against existing literature. Section 3.3.4 outlines some of the challenges to quantifying mitigation potential in the agriculture sector and explains in more detail when and why we relied on existing literature.

Mitigation estimates are given relative to the latest year of non-COVID historical emissions data (2019) and, where possible, are based on a range of scenarios of production growth. Livestock related mitigation options are evaluated in terms of improvements in emissions intensity, such as the intensity of enteric fermentation emissions in dairy production. Intensity improvements will only lead to a reduction in overall emissions if the output of the activity (e.g. tonnes of meat or dairy produced) remains the same. As many mitigation options to improve emissions intensity also improve the productivity of the system, there is commonly a rebound effect whereby absolute levels of emissions only marginally decrease, or may even increase, under scenarios of increased production. In our results, we therefore clearly state the assumptions under which the mitigation potentials are evaluated.

3.3.3.1 Data selection

Quantitative analysis for each country is based on either data derived from FAOSTAT, national inventory data, or national data derived from expert sources. FAOSTAT emissions data is calculated using IPCC's Tier 1 approach. For all countries, granular activity data on a year-by-year basis, is available. Yet, we used national data from the UNFCCC or from scientific literature, which calculates emissions using the more detailed, country-specific IPCC Tier 2 or Tier 3 approach where full datasets are available (Annex I countries to the UNFCCC, i.e. Australia, New Zealand, the UK and the US in our study) or there are large data discrepancies between FAO and national emissions. This approach is significantly more accurate for emissions from agriculture because it allows regional specification in terms of climate, soils, practices or animal categories whereas Tier 1 is a very coarse approach where a default emission factor is multiplied by the activity at country-level.

UNFCCC data is generally of higher quality than FAO data for developed countries due to the additional country specific information included. In general, differences between data sources are due to different emissions intensity factors used in the calculations which are combined with considerably more detailed activity data on a country level.

3.3.3.2 Reduction of the emission intensity of livestock

Emissions from livestock, particularly enteric fermentation, dominate farm-gate agricultural emissions in many countries. In our analysis, we focus on cattle dairy and beef systems since large ruminants are responsible for the highest share of livestock emissions. While enteric fermentation emissions from small ruminants and some other animals (e.g. buffalo) and manure management emissions from swine and poultry can be notable, we exclude them from quantification under this specific measure since cattle remains by far the most relevant emissions source (see section 3.3.3.3 for more discussion on manure management, including for other livestock).

Livestock emissions consist of four components – enteric fermentation, manure management, manure applied to soils, and manure deposited onto pasture[15]. In our analysis, we evaluate the

[15] Emissions, mainly of N_2O, also occur through fodder production, which is not part of the quantitative analysis.

mitigation potential through improvements in emissions intensity for two of these components – enteric fermentation and manure management. Emissions from manure applied to soils are quite small compared to total livestock emissions, and potential mitigation options fall more under the umbrella of improved nutrient management rather than livestock management. While emissions from manure left on pasture vary in magnitude, emissions are lower than in systems with managed manure treatment. It is also very difficult to reduce emissions from manure left on pasture short of reducing the number of cattle. We assume that the emissions intensity of manure applied to soils and manure left on pasture do not change in any of our scenarios.

Emissions from enteric fermentation primarily depend on feed intake. In general, the higher the feed intake, the higher the methane emissions. Methane production is, to some extent, also affected by the composition of the diet. Feed intake is positively related to animal size, growth rates, and production (e.g., high slaughter weights, milk production, wool growth, or pregnancy). Livestock emission intensities, especially for enteric fermentation, vary drastically between countries, and much more so for beef cattle than other livestock. Reasons for this variance include animal breed, animal health, diet, and the local environment (e.g. types of forage available, climatic conditions). Some of these factors can be affected by changes in management practices, such as changes in livestock diets or improvements to animal health, while some cannot. For example, cattle on pasture are dependent on the quality of forage on that pasture, which can be impacted by management practices but is also dependent on the local environment and climate.

There are inherent limits to how much emission intensities can be reduced by modifying practices because enteric fermentation is a fundamental part of cattle biology (Gerber et al. 2013). When this emission intensity is reached, further reductions are only feasible through reducing the number of livestock. In addition, high-intensity production systems with high efficiencies often depend on external feed and other supplement inputs that can cause significant indirect emissions from their production. Such indirect life-cycle emissions of feed and feed supplements could not be considered in this analysis. These considerations highlight the fact that shifting towards more plant-based diets in combination with targeted measures to reduce livestock, resulting in reductions in herd size, would have the largest impact on livestock emissions.

In estimating the mitigation potential for livestock systems, we compare current cattle meat and dairy emission intensities with that of other countries to get a high-level understanding of what magnitude of emission intensities can correlate to applying good practices. We then evaluate the mitigation potential if the country were to adopt good practices (such as health monitoring, breeding optimisation, or feed optimisation) and reduce emission intensities to “good practice” levels. We consider our estimates to be at the upper end of a range of estimated mitigation potentials as they may not fully take into account local limitations.

By implementing good practices, we assume that one of the main mechanisms for reducing the emission intensity of enteric fermentation (per tonne of product) are based on productivity improvements, which results in a reduction of animal numbers if total production remains constant. For instance, with healthier animals, fewer animals are needed to produce the same amount of meat and milk, thereby resulting in smaller herds and lower emissions for the same overall productivity. Improving cattle health also increases productivity through higher fertility rates and higher weaning (calving) rates, requiring less animals to produce the same number of offspring quicker, and allows cattle to gain weight faster by improving performance.

In each country for which we provide an evaluation of livestock mitigation potential, we do so for two scenarios, both under conditions of reaching good practices across all production systems with (1) assuming constant production at 2019 levels, and (2) assuming production increases following the 10-year historical trend until 2030. Both scenarios are applied to the four countries for which we quantify the mitigation potential – Argentina, Australia, Indonesia, and South Africa.

Together, these scenarios provide a range of possible mitigation potential that may be possible. The second scenario is used to highlight the possibility that reducing emissions intensity may have a rebound effect and lead to an overall increase in emissions if production patterns do not change. Furthermore, even with fixed productivity, there is a limit to emission reductions from intensity improvements alone and substantially reducing livestock emissions would rely on reducing the number of animals. Measures for reducing livestock numbers are highlighted as additional mitigation options.

In all our calculations, we assume that there is no shift in management systems within a country. That is, there is no shift in systems from mixed or grassland systems to more intensive farming practices. Intensive (feedlot) farming systems may have a significantly lower enteric fermentation emissions intensity since more meat is produced in a shorter time, but generally result in higher emissions from manure management since manure is collected rather than left on pasture. Shifting to intensive livestock production systems would result in an increased demand for animal feed. A significant extent of agricultural land is used solely to grow livestock feed, and the expansion of feed crop production is linked with deforestation. Feedlot systems also carry higher risks to animal health and welfare and may not be suitable in all contexts.

3.3.3.2.1 Data, country specific parameters, and implementation

In order to understand the global distribution of current cattle emission intensities, we calculated the emission intensities (EI) per tonne of product (meat or milk) for each relevant livestock subsector (enteric fermentation, manure management) for 197 countries or territories using FAO emissions and production data. A cut-off point was used to exclude countries with low meat (<50,000 tonnes) or milk production (<100,000 tonnes) from the statistics as the EIs for these countries were often outliers. We then calculated the global median, minimum, maximum and 20th percentile EIs to understand what could be achievable within the context of emission reductions (Table 3). Indirect life-cycle emissions from feed or feed supplement production and imports, associated land use change emissions, and direct emissions from fertiliser inputs on pastures in these production systems were excluded. This is particularly relevant for high intensity cattle meat production in developed countries, which has caused significant environmental pollution, ecosystem destruction, and substantial LULUCF emissions.

Dairy cattle systems are much more homogenous than meat systems and generally consist of pasture-based or mixed (grain-finished) systems. To calculate potential reductions in dairy emissions, we assumed that developing countries can reach the global median EI for enteric fermentation and manure management emissions. Current dairy EIs in Indonesia and South Africa are above the global median, so we calculated the mitigation potential for each country if global median emission intensities were to be achieved. Dairy EIs in Argentina are already well below the global median, so we left them unchanged from the baseline under the assumption that they were applying better-than-average practices. In Australia, dairy EIs are only slightly below the global median. The Australian dairy industry claims that dairy production already has very low emission intensities relative to global levels (Dairy Australia 2020). As a result, we left them unchanged from the baseline due to uncertainties in the extent of emissions reduction possible.

Table 3: Global meat and dairy emission intensities for high-producing countries

	Sub sector	Minimum	20th percentile	Median	80th percentile
Meat, cattle (tCO_2e/t meat)	Enteric fermentation	0.52	10.17	17.86	46.60
	Manure management	0.02	0.54	1.52	2.50
Dairy, cattle (tCO_2e/t milk)	Enteric fermentation	0.10	0.42	0.84	2.52
	Manure management	0.01	0.03	0.10	0.17

Source: For emissions data and FAO (2022b) for production data. Note that these statistics exclude countries with low meat (<50,000 tonnes) or milk (<100,000 tonnes) production levels, amounting to 96 countries analysed in total.

Table 4: Meat and dairy emission intensities for countries studied

	Sub sector	Argentina	Australia	Indonesia	South Africa
Meat, cattle (tCO_2e/t meat)	Enteric fermentation	26.42	14.60	43.17	19.50
	Manure management	0.02	0.71	1.13	1.07
Dairy, cattle (tCO_2e/t milk)	Enteric fermentation	0.31	0.12	6.64	1.77
	Manure management	0.49	1.46	0.51	0.27

Source: Production data from FAO (2022b). Emissions data for Argentina and Indonesia comes from FAO (2022), for Australia from Australian Government (2022) and from Tongwane & Moeletsi (2021) for South Africa due to high data discrepancies.

Emission intensities for beef systems are far more complex due to the stark differences in production systems. To account for heterogeneity in livestock systems, particularly in beef production, we also gathered FAO (2022a) data on regional emission intensities per livestock system and the percentage of meat produced by each system (feedlots, grassland, mixed).

We assumed a 20% reduction in the manure management EI for beef cattle across all the countries studied (based on potentials outlined in Gerber et al. (2013)), since there are more clear-cut ways to reduce emissions from collected and stored manure, and manure emissions are less dependent on the local conditions and biophysical limitations.

Where national data was unavailable, we applied a general approach to estimating the mitigation potential of reducing beef EI. For developing countries, in this case Indonesia, we assumed that feedlot systems applying good practices in livestock management would achieve the global average of feedlot's enteric fermentation EI value. For grassland and mixed systems, we made the assumption, based on our evaluation of FAO emission intensities data and related literature (FAO 2022a; Gerber et al. 2013), that developing countries can reach maximum enteric fermentation EI reductions of at least 30% below today's levels through applying good practices related to nutrition, health, breeding, and herd management. We applied these assumptions to the regional emissions factors and weighted them according to the systems' contribution to total meat production. For manure-related meat emissions, we applied the same 20% reduction since manure mitigation is highly dependent on the baseline.

In cases where literature illustrating the mitigation potential of the specific country's cattle sector was available, we opted to use that literature in place of the above, more general approach.

For Argentina, we assumed a 40% total reduction in enteric fermentation EIs based on the results from FAO and New Zealand Agricultural Greenhouse Gas Research Centre (2017). While this value is quite high, it is based on a national study that estimates improvements in the enteric fermentation EI of beef cattle production from specific measures (the controlling of reproductive diseases, the supplementation of breeding cows, and the strategic supplementation of steers) applied to different climatic zones (arid, subtropical, temperate). The above measures reduce emission intensities primarily through enhanced animal productivity. For instance, the strategic supplementation of cattle can lead to shorter finishing periods and/or higher slaughter weights and reducing enteric methane emissions per kilogram of live-weight. It is important to note that increased individual animal performance can generally result in higher absolute emissions if herd size does not decrease accordingly (ibid).

For South Africa, due to large discrepancies between FAO and national data, the baseline enteric fermentation EIs are derived from Tongwane & Moeletsi (2021), who provide country-specific estimates for cattle emissions divided into production systems. Since Australian and South African livestock production systems are very similar in terms of the environmental conditions and available feed types, we assumed that South Africa's beef enteric fermentation EI would be able to reach at least that of Australia's. Here it is worth noting that this is a technical potential and South Africa may require substantial investment and support to reach the same emission intensities. There is also the risk that the reduction in livestock emissions may be displaced by emission increases elsewhere, if additional inputs (i.e. grain feed, fertiliser) are required to achieve such emission intensities, resulting in higher indirect emissions from feed production and fertiliser application on pastures (i.e. to improve forage quality).

For Australia, current EI levels were based on national data, in which reported emissions from cattle are divided into three categories – dairy cattle, meat cattle raised on pasture, and meat cattle raised in feedlots. Assuming that Australian feedlot beef accounts for 34% of all cattle meat production (ALFA o.J.), we calculated the emission intensity for pasture and feedlot cattle. The enteric fermentation EI for feedlot cattle is rather low and has a similar magnitude to that of North American feedlot cattle, so we assumed that there is little room to improve Australian feedlot EIs beyond innovative measures. On the other hand, we assumed that cattle raised on pasture can reduce their enteric fermentation EI by 18% by employing efficiency strategies, including improved feed and cattle lifecycle management, based on Cusack et al. (2021). However, this does not account for the potential indirect emissions from feed production that may arise from increased grain supplementation.

While we did not estimate the mitigation potential of feed additives, they are discussed as an option to reduce enteric fermentation emissions in some of the analysed countries, particularly in developed countries with high levels of confined (i.e. feedlot) animals. In particular, *Asparagopsis* has been discussed as a future measure to drastically reduce emissions. However, significant open questions remain on the effectiveness of the measure in real-life, farm-wide situations, the impacts on animal and human health, and other environmental and cost implications of scaling up the production of red algae, e.g. large scale algae production in coastal areas could destroy coastal ecosystems of seagrass that are important for CO_2 sequestration., *Asparagopsis* may also be toxic to cattle in larger quantities and its effects on the taste of products is still being determined (Hegarty et al. 2021; Vijn et al. 2020). These aspects may reduce farmer's willingness to adopt the algae as feed supplement. One of the world's longest commercial trials of *Asparagopsis* found significantly lower methane reductions than previous experiments, recording reductions of 28% instead of the 80–96% (Readfearn 2023). Given the high uncertainties regarding efficacy and numerous animal health and environmental drawbacks, relying on technologies such as feed additives will not be sufficient to achieve climate targets and should not replace the deep reductions needed in ruminant meat production.

3.3.3.3 Manure management

Improved manure management involves the storage, utilisation, and treatment of on-farm animal waste in a way that minimises GHGs emitted. Most often this includes reducing the storage time of liquid manure by spreading it daily on farmland, covering anaerobic lagoons and capturing methane from them, or converting solid manure to aerobic compost (Drawdown o.J.). Anaerobic digesters are another option for manure management that is highly relevant in countries with high volumes of confined (i.e. feedlot) animals, such as the United States and China. Not only does it have high emissions reduction potential, but the process also results in biogas and digestate (i.e. fertiliser) production.

Since the way manure is managed varies on a farm-to-farm scale, it is challenging to provide a broad recommendation for what farmers in a certain country can do to reduce emissions from manure management. Although on an individual farm-level, the emission factors of different animal waste management systems can be compared to determine which measures are less emission-intensive (Gavrilova et al. 2019). As such, we have used existing literature sources to estimate the mitigation potential for improved manure management in China and the United States (Davison et al. 2023; Dong et al. 2022; Eagle et al. 2022; Roe et al. 2021).

3.3.3.4 Silvopastoral systems

Silvopastoral systems combine tree species with livestock farming activities on grassland or native forest. The integration of trees results in increased carbon sequestration potential on pasture (Australia, New Zealand), while the integration of livestock in forests reduces pressure on agricultural expansion and results in avoided emissions from deforestation (Argentina).

In the case of Argentina, the establishment of silvopastoral systems, referring to cattle rearing on forest plantations, would not negatively impact forest biomass when they are established on low-carbon stock forests (while avoiding high-carbon stock, old growth forests). Forest biomass can also be protected from degradation by preventing overgrazing (e.g. rotational grazing practices). Silvopastoral systems usually result in improved forage quality and animal productivity, but this was not quantified (CIWF 2017).

We used existing literature to estimate the mitigation potential for Argentina (Gonzales-Zuniga et al. 2022). To calculate the mitigation potential of silvopastoral systems for Australia and New Zealand, we used the following assumptions (Table 5):

Table 5: Main assumptions in quantifying policy impacts – silvopastoral systems (AUS, NZL)

	Assumptions	Source / comments
Carbon sequestration potential	NZL: 1.72 tCO_2e/ha/yr AUS: 2.90–3.85 tCO_2e/ha/yr	NZL: New Zealand Ministry for the Environment (2021) – page 11, average carbon stock value of grassland with woody biomass in

	Assumptions	Source / comments
		transition divided over a 28-year period AUS: Feliciano et al. (2018), Table 3 for lower end of range; Donaghy et al. (2009) for upper end, extracted 20-year average from Figure 25
Share of area under silvopastoral systems	10% increase from baseline	n/a

Source: Authors' own compilation.

3.3.3.5 Improving grassland sequestration potential

The carbon sequestration potential, and in turn emission intensity, of grassland can potentially be improved through measures such as planting deep-rooted grasses, adding legumes, improving forage quality (through nutrient and water management), fire management, and managing the frequency and intensity of grazing livestock (Garnett et al. 2017). This study focused on the potential of grazing management to increase grassland carbon sequestration, primarily through restoring degraded pastures with low carbon stocks. This practice can also result in lower cattle emissions due to improved productivity and forage quality.

Due to high uncertainties in long-term soil carbon sequestration dynamics and the complex interactions with livestock productivity, this mitigation option was not quantified using the PROSPECTS+ tool. Instead, we used literature values (United States) (Chambers et al. 2016; Fargione et al. 2018) or a simple calculation (potential additional CO_2 sequestration per hectare * hectares of grassland to which measure could be applied) (Australia, Brazil, South Africa) to estimate the mitigation potential. For grassland restoration measures that include pasture fertilisation, it is also important to consider the potential increase in nitrous oxide emissions resulting from increased fertiliser application.

3.3.3.6 Improved nutrient management – fertiliser use

There are several options available to reduce the extent of synthetic fertiliser application and subsequently, emissions from their overuse. In general, nutrient management could be improved by achieving an optimal Nitrogen Use Efficiency (NUE) (in most cases, 70%) by applying synthetic fertilisers according to the 4 Rs – right place, right time, right source, right rate.

Since nutrient management varies on a farm-to-farm scale, it is difficult to provide a broad recommendation for the measures at global level, because recommendations depend on fertilisation practices and crop rotations at individual farm level. In general, farmers should focus on achieving an optimal NUE to avoid nitrogen losses. However, calculating the NUE is farm-specific and requires extensive granular data. As such, we have used existing literature sources to estimate the mitigation potential for improved nutrient management in China, Egypt, and the United Kingdom (China Agricultural University 2022; Chen et al. 2022; Fargione et al. 2018; Roe et al. 2021; UCL 2021).

3.3.3.7 Improved nutrient management – cover crops

The inclusion of cover crops leads to an average increase in soil organic carbon (SOC) stocks, which increases carbon sequestration rates on cropland. Cover crops also decrease soil Nitrate-

N levels, contributing to reduced emissions from managed soils (indirect emissions from synthetic fertiliser and crop residues).

The United Kingdom has done substantial work on the estimating the mitigation potential of the agricultural sector, including for specific measures such as cover crops. We opted to use government estimates and supplemented them with other literature sources or our own calculations (Eory et al. 2020; UCL 2021).

3.3.3.8 Rice cultivation

Emissions from rice cultivation can primarily be reduced by shifting from continuous flooding to alternative wetting and drying irrigation systems. The System of Rice Intensification (SRI) is another measure that includes changes in flooding patterns; this measure also puts an emphasis on reducing synthetic fertiliser use and improving straw residue management.

This mitigation option was not quantified with the PROSPECTS+ tool due to high uncertainties in associated nitrous oxide emissions. While intermittent flooding systems definitively reduce methane emissions from rice production, the shift in systems also leads to an increase in nitrous oxide emissions. Nitrous oxide emissions could be three times higher than previously reported, meaning efforts to mitigate methane can significantly increase nitrous oxide emissions. No major rice-producing countries report rice-N_2O emissions in their national inventories (Kritee et al. 2018). While there is some uncertainty as to what extent these estimates consider these nitrous oxide emissions, we used literature values to estimate the mitigation potential of improved rice cultivation practices for China, Egypt, and Indonesia (China Agricultural University 2022; Prabhakar et al. 2010; Roe et al. 2021; Wang et al. 2022).

3.3.3.9 Improve intensification of crop production

Primarily in the Global South, many crop or livestock production systems have rather low productivity. Improving outputs per hectare on existing land can reduce the pressure for agricultural expansion and avoid emissions from the deforestation needed to otherwise meet increasing demand. In Indonesia, this is particularly relevant for palm oil production while Brazil could improve the productivity of both soybean and cattle.

The applicable measures to bridge yield gaps are dependent on the specific circumstances of the farm (e.g. soil conditions, rainfall, current farming practices, etc.), but can include improved soil and water management, adjusted harvesting techniques and field maintenance, better crop protection, and improved nutrient management (Marin et al. 2022; Monzon et al. 2021). The latter measure could potentially result in emission growth from increased fertiliser application, which should be monitored.

Due to the challenges with obtaining extensive LULUCF data from non-Annex 1 countries and the complexities in attributing land use change emissions to certain activities, we used literature values to estimate the mitigation potential from improved crop productivity for key agricultural commodities (soy in Brazil, palm oil in Indonesia) (Marin et al. 2022; Monzon et al. 2021). Most of the mitigation potential for both countries is derived from avoided emissions from deforestation, and peatland conversion and fires in Indonesia's case, relative to a 2030 reference scenario. The estimates do consider the emissions resulting from intensified agriculture (i.e. increased fertilisation), which are minute compared to the mitigation potential from avoided land-use conversion which is in the hundreds of megatons.

3.3.4 Reflections on the quantification methods

The total mitigation potential of the agriculture and LULUCF sectors, as well as the potential of individual measures, is rife with uncertainties. The IPCC reports the mitigation potential of the agricultural sector to be between 1.6–28.5 $GtCO_2e$ (Figure 9Nabuurs et al. 2022b). Most of the uncertainty is derived from carbon sequestration measures including soil carbon management in croplands and grasslands, agroforestry, and biochar. Mitigation measures solely focused on reducing methane and nitrous oxide emissions have a reported mitigation potential between 0.5–3.2 $GtCO_2e$.

Figure 9: Global agriculture mitigation potential from carbon sequestration and non-CO_2 sources

Mitigation option	Estimate type	<USD20 tCO_2-eq^{-1}	<USD50 tCO_2-eq^{-1}	<USD100 tCO_2-eq^{-1}	Technical
Agriculture total	Sectoral	0.9 (0.5–1.4)	1.6 (1–2.4)	4.1 (1.7–6.7)	11.2 (1.6–28.5)
	IAM	0.9 (0–3.1)	1.3 (0–3.2)	1.8 (0.7–3.3)	ND
Agriculture – Carbon sequestration (Soil carbon management in croplands and grasslands, agroforestry, and biochar)	Sectoral	0.5 (0.4–0.6)	1.2 (0.9–1.6)	3.4 (1.4–5.5)	9.5 (1.1–25.3)
	IAM	ND	ND	ND	ND
Agriculture – Reduce CH_4 and N_2O emissions (Improve enteric fermentation, manure management, nutrient management, and rice cultivation)	Sectoral	0.4 (0.1–0.8)	0.4 (0.1–0.8)	0.6 (0.3–1.3)	1.7 (0.5–3.2)
	IAM	0.9 (0–3.1)	1.3 (0–3.2)	1.8 (0.7–3.3)	ND

Source: Nabuurs et al. (2022, p. 776)

A first source of uncertainty in estimating the mitigation potential is the considerable uncertainty in current emissions and sinks in agriculture and LULUCF. For instance, data sources for emissions in the agricultural sector vary considerably between sources depending on the methodology used in terms of tier level, corresponding emission factors and activity data used, and should be further refined (Nabuurs et al. 2022).

Land use data presented in national greenhouse gas emissions inventories (NGHGIs) has numerous uncertainties as well. There is currently incomplete reporting on land use and carbon pools, particularly on non-forest land in developing countries. They also may not fully consider human-induced environmental changes when using outdated data. Additionally, NGHGIs might exclude certain fluxes on managed land if they lack specific methodologies or are considered non-anthropogenic, such as drained organic soils (Grassi et al. 2023).

In general, there are several challenges to approaching LULUCF data. Improved monitoring of the land CO_2 balance, via technologies such as remote sensing as well as on-the-ground efforts, is needed to provide more accurate emissions and sink estimates. Particularly for soil carbon and non-forest land in developing countries, observation-based estimates are often lacking, resulting in unaccounted for carbon fluxes (Nabuurs et al. 2022). In addition, most non-Annex I countries do not differentiate between managed and unmanaged forest land, resulting in inconsistent or incomplete estimates, and further capacity building is needed to fill these gaps (Grassi et al. 2023).

There is further uncertainty as to how future climate change impacts will affect the potential and permanence of mitigation measures, such as changing weather pattern impacts on soil carbon storage and water availability.

Secondly, agricultural systems of countries are very complex, and the practices on one farm can be significantly different from its neighbouring farm. For example, differences in on-farm manure management or nutrient management, practices can notably affect the mitigation potential of corresponding measures. It is difficult to apply a one-size-fits-all approach since solutions should be tailored toward individual farms. In the LULUCF sector, it is difficult to attribute deforestation to certain activities, since land use dynamics are complex and often overlap one another (e.g. timber and agricultural expansion).

The same complexities are apparent in the livestock sector. Livestock production systems can generally be divided into three categories – feedlots, mixed systems, and pasture-based. There are marked differences between, as well as within, systems in terms of feed and forage intake (shares of each, makeup, quality), health and reproductive status, and the potential for improvements.

Thirdly, the data available is often not sufficient to accurately estimate the mitigation potential. For example, while improved rice cultivation practices result in methane emissions reductions, it can also lead to an increase in nitrous oxide emissions. However, as no countries report nitrous oxide emissions from rice cultivation in their GHG inventories, it is difficult to estimate its potential impact. Similarly, LULUCF emissions data is often limited in non-Annex 1 countries.

Finally, some of the countries studied in this project are geographically large, spanning several climatic zones and environmental conditions with implications for the biological processes underpinning the emissions investigated and diverse agri-climatic conditions. For example, forage of different kinds of qualities are available to pasture-based livestock in different areas of the country, different soil types can impact options for crop systems, or water availability for irrigation may impact management practices that can reasonably be implemented.

For the above reasons, estimating mitigation potential at the national level across a range of different farming practices carries substantial uncertainties. Establishing a precise mitigation potential estimate on a national level requires extensive data combined with local knowledge of practices employed across the country. In many cases, that data does not yet exist.

The mitigation potentials reported in the country dossiers should be approached with caution. While they can provide a general order of magnitude of potential for the measures explored, numerous uncertainties and questions on effective implementation must be considered. Nevertheless, the mitigation actions proposed would lead to more sustainable practices overall and remain valid options for countries to consider implementing.

4 Barriers for ambitious mitigation in the agricultural sector

4.1 Findings from the literature

A myriad of different barriers obstruct mitigation in the agricultural sector. The IPCC Special Report on Climate Change and Land 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, for example, low world market prices, established infrastructure, lack of sales markets for climate-friendly foods 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.

These barriers can be clustered according to the relevant governance level for taking action, while taking into account the IPCC classification of barriers as outlined above. 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 and approaches for overcoming existing barriers will therefore need to be context-specific (Wreford et al. 2017; IPCC 2019).

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

- Economic barriers
  - The **lack of specific economic benefits** to farmers acts 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 as well (Wreford et al. 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 (Wreford et al. 2017; Wageningen University 2014). This has also been identified as a barrier to reducing food loss and waste at the farm level (FAO 2019). **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 farmer's age or farm size,** that will impact the likelihood of implementing innovations (Wreford et al. 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 (Wreford et al. 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

- 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. maintaining unsustainable burning practices of agricultural waste in India, China and South-east Asia (Bhuvaneshwari et al. 2019) changing crop management, implementing agroforestry practices or reducing GHG emissions from rice cultivation.

▶ Socio-cultural barriers

- Further factors at farm level relate to **personal attitudes, traditions and practices** which will impact the acceptance of mitigation measures (Wreford et al. 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 the access to information (Aryal et al. 2020). Particularly in the context of smallholder farming, the social and cultural role of livestock rearing, and 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 South East 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).

▶ 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. to change cultivation practices (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 (Wreford et al. 2017). If deforestation brings economic advantages, political will may be weak to implement stricter regulation (Kalaba 2016). **Economic objectives to increase agricultural outputs** 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 (Wreford 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 (Wreford et al. 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 as well. 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 2019). 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. 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 (Wreford et al. 2017; Bispo et al. 2017).

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

▶ 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 (Wreford et al. 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 those practices will be available (Wreford et al. 20172017). This can result from a **lack of a goal or vision of sustainable agriculture** that is preventing coherent policy incentives for sustainable practices (Oberč and Arroyo Schnell 2020). 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).

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 will put this country at disadvantage in the competition with others (Wreford et al. 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 which 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 may mean that farmers cannot afford to harvest surplus food (WWF 2021). Power imbalances between farmers and retailers are structural drivers that keeps 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).[16]
- **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 (Oberč und Arroyo Schnell 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, 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).
- 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 (Kachi et al. 2021).

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** and with **social and cultural habits** and is therefore politically sensitive. Additionally, the benefits of sustainable diets have so far not been sold 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 appearance of especially fruits and

[16] 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 and 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.

4.2 Barriers and challenges to achieving mitigation potential in ten selected countries

The key barriers to implementing measures to achieve the mitigation potential in each country were identified by building on the analysis presented in chapter 43 above. Barriers are again clustered according to the policy level at which they occur – farm, national, international, or consumer. We also continue to use the IPCC framework of distinguishing between technical, economic, institutional, legal, policy, social and environmental barriers. This analysis was used to provide an overview of possible barriers, that is a starting point for identifying relevant barriers for each country.

To select specific barriers, we identified those that are relevant to the specific national context, those identified in the literature relevant to specific mitigation options, and additional literature sources that assessed broader agricultural mitigation policy barriers in the country.

In our analysis, we observed that many of these barriers apply to all countries and, vice versa, most countries experience multiple barriers to mitigation. Where we do see differences in barriers experienced by countries, it is usually due to their socio-economic circumstances and farming set-up (smallholder or more industrial). For example, food culture and tradition being a limit to changing diets and being politically sensitive is one likely experienced in most countries. A lack of information and knowledge on the benefits of mitigation, particularly at the farm level, is also common. However, issues of land tenure and property rights, or access to finance are more commonly experienced in developing countries.

5 Conclusions

5.1 Conclusions on mitigation potentials in the light of country-specific contexts

This report summarises the key messages of ten country dossiers and qualitatively discusses major climate change mitigation potentials, their uncertainties and related barriers in the agricultural sector, with a focus on interventions on the production side. Sustainable agricultural production is not only critical for climate change mitigation, but also for safeguarding a healthy, nutritious diet for present and future generations. Current food production levels are sufficient to feed the world, but approx. 10% of the population faces severe levels of food insecurity. The just distribution of agricultural products, which is not part of this research but nevertheless recognised as essential, can already contribute to these goals. Coupled with a transition to sustainable production practices, it is possible to substantially decrease emissions from the sector while ensuring food supply for all (FAO et al. 2023).

Analysing and comparing the mitigation potentials and challenges to implementation across the ten countries illustrates the importance of tailoring the solutions to different countries, regions and circumstances, particularly in the agricultural sector. **Agricultural systems extremely diverse and often very closely linked to cultural aspects of societies, and of course geographical and climatic conditions.** The country reports attempt to quantify mitigation potentials for large-scale agribusiness, smallholder farming, as well as for subsistence farming, and across all agricultural activities – all facets of the sector should be addressed to maximise mitigation efforts in the sector, and it is clear that a one-fits-all approach will not work in this context.

The country reports look at different mitigation options for each country, depending on the feasibility and relevance of different areas in terms of mitigation potential but also sociological and economic benefits. 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.

We find that stopping agricultural expansion to avoid deforestation, particularly in tropical countries (e.g. Brazil and Indonesia), has the highest impact on emissions of all single mitigation options. To address emissions from enteric fermentation as a key emission source, in most countries demand-side measures to reduce domestic consumption of animal products and/or transition economies with high dependencies on exports of animal products have major mitigation potentials. Such measures could be guided by additional policy targets to reduce production volumes/livestock numbers (e.g. limiting livestock numbers per area). However, this is contrary to political aims to increase livestock production in several countries, may tackle sensitive national circumstances (cultural consumption patterns, threats to food security etc.) and thus faces substantial economic, political and socio-economic barriers. Nevertheless, emissions from enteric fermentation and other livestock-related emissions are difficult to fully mitigate if production volumes are not changed. We find that in many cases, the targeted increase in livestock production in the future would offset any emissions reductions from improved livestock management and feed systems (e.g. Australia and Argentina). While the mitigation potential of certain agroecological practices like cover crops and crop rotation is estimated to be rather limited based on the literature, they provide numerous co-benefits (see below), including adaptation to climate change impacts, and are no-regret measures that can be widely implemented.

While this project focuses on mitigation in agricultural production, it is essential to highlight that without changes also to dietary patterns, mainly in developed countries, a sustainable and just 1.5°C pathway is not feasible. Discussing alternative narratives next to current plans for agricultural expansion plans could help appreciate the implications of a shift to largely plant-based diets and potentially avoid disruptions in the sector in the medium to long term. Food waste causes unnecessary GHG emissions through the agricultural production of unused food products and through methane emissions from waste management, and reducing food waste levels across the supply chain could result in significant avoided emissions. International research reports that demand-side measures, such as shifting to less meat intensive diets and reducing food waste, have a high mitigation potential while contributing to other co-benefits at relatively lower costs (Roe et al. 2021).

The country dossiers also illustrate numerous additional benefits beyond reducing and avoiding GHG emissions from the suggested measures: Supporting the rights and land tenure of indigenous people, fostering biodiversity, improving soil health and productivity, water savings, longer-term security in agricultural yields, higher-value products, economic and social benefits to rural livelihoods, and reducing local environmental pollution are just some of the benefits of different mitigation actions.

While land-based mitigation **measures that increase carbon sequestration on agricultural land** are an attractive option that can have quite high sequestration potential (e.g. grassland restoration, agroforestry/silvopastoralism), there are many risks and uncertainties as to their effective implementation. Natural carbon sequestration measures should not replace the decarbonisation needed in the agricultural sector to meet climate targets and 1.5°C compatible emissions levels, let alone serve to "offset" emissions in other sectors. However, due to their numerous co-benefits, and their effectiveness as a climate change adaptation measure, they **should continue to be supported and implemented**.

There are significant difficulties to quantifying mitigation potentials in the agricultural sector. Agricultural production systems are complex and vary on a farm-to-farm level, and it is challenging to generalise mitigation options across an entire country since their potential depends on a multitude of factors. For instance, livestock systems can improve their emissions intensity through varying measures, but their mitigation potential is highly dependent on the specific production system (e.g. feedlot, grassland), the current production efficiency, and the geo-climatic circumstances, and it is difficult to compare across countries. In addition, it is difficult to find the granular data needed to perform analysis at the national level, particularly in non-Annex I countries.

5.2 Patterns of barriers to realise mitigation potentials and related recommendations

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.

A common challenge across the countries considered is the lack of information on mitigation options and their benefits amongst farmers, and the lack of access to financing for up-front investments. Knowledge dissemination **on sustainable practices, coupled with financial incentives,** could often incentivise mitigation actions. 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. 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 (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. 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) (Oberč und Arroyo Schnell 2020). Systems of graduated payments rewarding farmers for increasingly better performance have shown to be more prone to promoting climate change mitigation than setting minimum environmental standards. Also, support should enhance innovation by, for example, promoting new technologies that have the potential to become self-sustaining if used more widely (World Bank 2020).[17]

In most of the countries analysed, agricultural policies, including production targets and striving for self-sufficiency, are currently decoupled from climate targets. Usually, different ministries are responsible for these two aspects, and in most countries, there are separate strategies to achieve the respective targets. **Integrating climate objectives and targets for future agricultural production could foster mitigation actions in the agricultural sector** and address the need for more resilience of the sector in the light of rapidly worsening climate impacts. Engagement of sub-national 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 (Gerber et al. 2013). Better coordination between health, agriculture, water and environment departments is also needed to ensure coherence among policies affecting sustainable diets (WRI 2016; FAO et al. 2021), and our analysis finds policies to change dietary habits are mostly absent in government strategies. **Specifying the role of agriculture in achieving national long-term climate targets provides an opportunity to raise ambition to tackle the emissions related to food systems**. So far, long-term strategies 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 stakeholder 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 existing barriers also call for a reform of agricultural subsidies, away from maximising output but focusing on quality and sustainability. For high-income countries, harmful support needs to be abolished by incorporating conditionality mechanisms in subsidy-schemes and avoiding reverting to distorting measures even in times of crisis. Support should not be coupled to production 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

[17] Revenues from carbon credits 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 Siemons et al. (2023a); Böttcher et al. (2022) undermines their suitability to represent a genuine option for offsetting emissions occurring elsewhere.

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 technology improvements and infrastructure have been identified as priority approaches for these countries. Consumer subsidies accompanied by well-designed social protection schemes could support health 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 with greater benefits for society as a whole (FAO et al. 2021).

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).[18] 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 sent 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 at which meals are publicly provided (Willett et al. 2019). **Reforms to improve tenure security** can avoid deforestation and unsustainable agricultural practices, though this is a sensitive issue (Angelsen 2010; Böttcher et al. 2021).

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) and the UNFCCC bring the global community together to do so (FAO et al. 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. Farmers need to be paid **fairer prices** in order to be able to improve harvesting and field management techniques. Cartels related to food production and trade and financial speculation on food have strong negative effects on populations in low-income countries that depend on global markets (Mbow et al. 2019). 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). The WTO can play a central role in coordinating members to take concerted efforts to reduce distorting agricultural measures while at the same time support the transition to sustainable food systems.

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 avoid deforestation (European Parliament 2020; Hughes and Terazono 2020). Developing multilateral public-private partnerships to engage diverse stakeholders while

[18] For example, 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)).

synergising public policies with private zero-deforestation and supply chain initiatives would be one approach to addressing deforestation (Furumo and Lambin 2020).

At consumer level, mostly socio-cultural and economic barriers play a role in the selected countries. **Education and knowledge as well as societal dialogue processes and guiding principles** are key drivers for overcoming such barriers. Advocacy and education are also necessary to promote knowledge on food loss and waste as an incentive to change behaviour. While fining stakeholders in the hospitality sector for their food loss and waste, as occurs in China, is another possible approach. 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).

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.

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. 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 re-think our approach and our attitude to agriculture instead of focusing only on technical solutions. Engagement from governments, companies, producers and consumers is necessary to achieve this, supported by an agenda set at the international level.

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