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Reducing greenhouse gas emissions in the global food system

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Key messages

- **Food system emissions are critical**: The global food system contributes 29% of all anthropogenic GHG emissions, with AFOLU accounting for 18% of global emissions. Non-AFOLU emissions (energy, waste, industry) – which are often overlooked – add 11% and are becoming the dominant source of food system emissions in developed countries.
- **Avoiding aggregation bias**: Grouping some emission sources into broad categories while breaking down others can obscure the importance of the smaller but often significant sources. Targeting these smaller sources, or 'low-hanging fruit', can effectively accelerate emissions reductions.
- **Closing data gaps**: A lack of detailed data on land use and food system emissions hinders the identification of high-impact mitigation strategies. More granular, reliable data collection at national and subnational levels is essential for effective policymaking.
- **NDC segmentation**: NDCs are organized around the four economic sectors (AFOLU, energy, IPPU and waste) in the IPCC Guidelines for National Greenhouse Gas Inventories. This hinders the development of integrated policies to reduce GHG emissions in the food system, which spans across these four sectors.
- **Collaboration, engagement and research are key**: Strengthening national research and fostering collaboration across civil society, governments, academia and the private sector are vital to creating context-specific, sustainable policies that address climate-change mitigation and adaptation without threatening food security, particularly for vulnerable populations.

Introduction

Agriculture and forestry cover almost 70% of the Earth's total land area.[3] Agriculture, forestry and aquaculture produce the primary biomass that everybody needs to make food, feed, fibres, shelter, energy and other biomaterials. Sixty percent of the global population – including 1.2 billion poor, rural people – depend mainly on agrifood systems for their livelihoods (FAO 2022). Agriculture represents around 70% of total freshwater withdrawals.[4] Therefore, there can be no sustainable future without sustainable agriculture and food systems.

However, the social and environmental costs of currently unsustainable food systems[5] overshadow, by far, their economic benefits. While the latter have been estimated in the range of USD 7–8 trillion (EcoNexus and Berne Declaration 2013), the former could reach as much as USD 15 trillion a year, including a burden of at least USD 11 trillion placed on human health, and USD 3 trillion on the environment (Nature 2019; Ruggeri Laderchi et al. 2024). Since 2000, the use of pesticides has surged by 62%, and the application of inorganic fertilizers has increased by 44% (FAO 2023). As a result of current practices, about 33% of the world's soils are degraded, with 52% of agricultural land experiencing soil degradation; some 20% of global aquifers are at risk of depletion (Jasechko and Perrone 2021); and 34% of fishery stocks are overexploited (FAO 2020). Nearly 75% of human-caused negative impacts on terrestrial biodiversity can be attributed to agriculture, while forestry represents an additional 23% (UNEP 2024). Primary forests continue to be destroyed at a rate incompatible with a pathway to zero deforestation (Forest Declaration Assessment Partners 2024), and agriculture directly threatens 86% of species at risk of extinction (Benton et al. 2021). As outlined in this publication, beyond these important environmental impacts, the global food system is a major source of greenhouse gas (GHG) emissions: it is responsible for about one-third of total anthropogenic emissions and plays a significant role in climate change.

To address the need for transforming the global food system in ways that reduce GHG emissions while maintaining food security and nutrition, we analyse global food system emissions from different data sources, namely the Emissions Database for Global Atmospheric Research (EDGAR), FAOSTAT and the Intergovernmental Panel on Climate Change (IPCC).

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3 See FAOSTAT: https://www.fao.org/faostat/en/#data/RL (last update 19 August 2024).

4 See World Bank – World Development Indicators database, see: https://databank.worldbank.org/reports.aspx?source=world-development-indicators (last update 19 September 2024).

5 By the definition of the High-Level Panel of Experts on Food Security and Nutrition (HLPE 2014), a food system combines "all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes."

> **Box 1. Low-Emission Food Systems Initiative of the CGIAR**
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> The Low-Emission Food Systems Initiative,[6] launched under the Consultative Group for International Agricultural Research (CGIAR) in 2022, takes a holistic view of food system emissions, covering the entire supply chain in selected partner countries. It explores underutilized pathways to reduce GHG emissions while improving food security and nutrition. Collaborating with national stakeholders – including civil society, governments, academia and the private sector – the initiative provides tools and knowledge to support evidence-based decisions, addressing challenges in policy development and implementation to cut GHG emissions from food systems.

We then recommend strategies for policymakers to better incorporate food systems into updated Nationally Determined Contributions (NDCs) aligned with the 1.5°C climate pathway. A thorough examination of food system emissions data is crucial for crafting effective policies that can swiftly and efficiently mitigate emissions. This global analysis is supported by similar analyses that have been conducted at the national level in four countries: China (Song et al. 2023), Colombia (Martius et al. 2023a), Kenya (Martius et al. 2023b) and Vietnam (Martius et al. 2023c). This work is part of the Low-Emission Food Systems Initiative of the CGIAR (Box 1).

Global food system emissions data

Emissions Database for Global Atmospheric Research (EDGAR)

The European Union's Emissions Database for Global Atmospheric Research (EDGAR) provides annual emissions data across regions, countries and sectors, not only for GHGs (CO_2, CH_4, N_2O and fluorinated gases) but also for air pollutants. The latest version of the dataset (EDGAR v8.0) covers the period 1970–2022.[7] The EDGAR Food dataset, focusing on food system emissions, was developed based on a previous version (EDGAR v6.0). It covers the period 1990–2015. EDGAR Food also includes land use and land-use change emissions data, taken from FAOSTAT.

According to EDGAR Food, global food system emissions amounted to about 18 [range: 14–22] $GtCO_2eq$/yr in 2015, that is 34% of total anthropogenic GHG emissions (Crippa et al. 2021). Emissions from agriculture, land use and land-use change accounted for 71% of total food system emissions, with the remaining part coming from pre- and post-production activities along food value chains, including industrial processes and packaging; storage and transport; as well as retail and consumption. Industrialized countries were responsible for 27% of global food system emissions, while the remaining 73% was emitted by developing countries (including China). While the land-based sector's share of food system emissions remains preponderant in developing countries (73%), food value chains' emissions beyond the farm gate – including industry and waste – now represent the larger part of food system emissions in industrialized countries (53%), surpassing land-based emissions (Crippa et al. 2021).

FAOSTAT

The FAOSTAT dataset, developed by the Food and Agriculture Organization of the United Nations (FAO), compiles detailed national-level annual data from 1961 to the most recent year available on agriculture and forestry (area, production and trade), agricultural inputs, as well as land use and land-use change, plus a suite of indicators on food security and nutrition. FAOSTAT also reports agrifood system GHG emissions, by gas and source of emission, following the standard IPCC methodology and Tier 1 emissions factors. Agrifood system emissions in FAOSTAT are divided into three main categories (land-use change; farm gate; pre- and post-production activities beyond the farm gate), and are further divided into different sources of emissions, as illustrated in Table 1.

In 2021, according to FAOSTAT, major sources of agrifood system emissions were, by decreasing order of importance: net forest conversion (18.1%), enteric fermentation by cattle (17.6%) and waste disposal (7.9%). The land-based sector (land-use change and farm gate emissions) still represented the bulk of food system emissions (67.1%). However, the share of emissions from pre- and post-production activities in total food system emissions has increased over the past decade: according to FAOSTAT, it represented 32.9% in 2021 (Table 1). Therefore, these emissions beyond the farm gate – in pre-production (provision of farm inputs, such as seeds, fertilizers, farm machinery and equipment) and post-production activities along food value chains all the way to the consumer table and wastebin – should not be overlooked.

Intergovernmental Panel on Climate Change (IPCC)

Following the IPCC (2006, 2019) methodological guidelines, GHG emissions in IPCC assessments or in national inventories used in Nationally Determined Contributions (NDCs) are usually measured, analysed, presented and

6 See: https://www.cgiar.org/initiative/low-emission-food-systems/

7 For more information, see: https://edgar.jrc.ec.europa.eu/emissions_data_and_maps

Table 1. FAOSTAT agrifood system emissions estimates (2021)

World agrifood system GHG emissions (2021)	MtCO2eq/ yr (AR5)	%
Agrifood systems (= I + II + III)	16,227.5	100.0%
I. Land-use change	3,101.2	19.1%
Fires in humid tropical forests	135.7	0.8%
Fires in organic soils	20.5	0.1%
Net forest conversion	2,945.1	18.1%
II. Farm gate	7,792.2	48.0%
Burning - Crop residues	37.9	0.2%
Crop residues	195.9	1.2%
Drained organic soils (CO_2, N_2O)	922.1	5.7%
Enteric fermentation	2,863.2	17.6%
Manure applied to soils	162.9	1.0%
Manure left on pasture	777.7	4.8%
Manure management	397.0	2.4%
On-farm energy use	928.5	5.7%
Rice cultivation	686.2	4.2%
Savanna fires	221.2	1.4%
Synthetic fertilizers	599.7	3.7%
III. Pre- and post-production	5,334.1	32.9%
Agrifood systems waste disposal	1,281.3	7.9%
Fertilizer manufacturing	466.4	2.9%
Food household consumption	1,204.5	7.4%
Food packaging	316.4	1.9%
Food processing	659.0	4.1%
Food retail	762.3	4.7%
Food transport	555.6	3.4%
Pesticide manufacturing	88.7	0.5%

Source: FAOSTAT: https://www.fao.org/faostat/en/#data/GT (last updated 9 November 2023, accessed 24 October 2024).

addressed according to four economic sectors: Energy; Industrial Processes and Product Use (IPPU); Agriculture, Forestry and Other Land Use (AFOLU); and waste. This sectoral approach, however, risks reducing the importance of cross-sectoral issues, dynamics, synergies and trade-offs in the political agenda. This is why, for the first time, the latest IPCC assessment report (AR6) included a specific chapter (Babiker et al. 2022) focusing on these cross-sectoral issues, including food system GHG emissions.

Based on calculations using the EDGAR (v6.0) and FAOSTAT datasets and methodologies described in previous studies (Crippa et al. 2021; Tubiello et al. 2021), the IPCC had estimated 2018 global food system emissions at 17 $GtCO_2eq/yr$ (Babiker et al. 2022). Agriculture, which includes crop and livestock production, was the largest contributor, responsible for 6.3 $GtCO_2eq/yr$ or 37% of total food system emissions. This was followed by land use, land-use change and forestry (LULUCF; 4 $GtCO_2eq/yr$ – 24%), energy use (3.9 $GtCO_2eq/yr$ – 23%), waste management (1.7 $GtCO_2eq/yr$ – 10%) and industrial processes within the food industry (IPPU; 0.9 $GtCO_2eq/yr$ – 5%) (Table 2). AFOLU emissions (livestock, crop production and LULUCF) amounted to 19% of total net anthropogenic emissions, and non-AFOLU emissions (energy, waste and IPPU) accounted for 12%.

Although the AFOLU sector had traditionally been seen as representing over 70% of food system emissions (Mbow et al. 2019; Crippa et al. 2021), the share of total non-farm food system emissions – which span across all other non-AFOLU economic sectors (i.e., energy, waste and IPPU) assessed by the IPCC – increased from 28% in 1990 to 39% in 2018 (Babiker et al. 2022).

It is also worth noting in Table 2 that food system emissions beyond the farm gate – i.e., from non-AFOLU sectors – amount to 6.5 $GtCO_2eq/yr$ in 2021, on par with agricultural emissions. Hence, to efficiently reduce food system emissions, it is critical to adopt an integrated perspective along the whole food supply chains (pre-production, on-farm and post-production activities, including waste management and disposal), and across the four IPCC economic sectors (Pingault and Martius 2023).

Table 2 also compares food system emissions with global net anthropogenic emissions. Babiker et al. (2022) had cited these as 54 $GtCO_2eq/yr$, yet the more likely global net anthropogenic emissions in 2018, the year for which the Babiker data were collected, is 59 ± 6 $GtCO_2eq/yr$ [8] (Riahi et al. 2022). It follows that food system emissions would be only 29% of total anthropogenic emissions, with a range of 24%–35%.[9] This is slightly lower than previously accepted, yet still substantial enough to warrant urgent action on food system emissions.

The share of AFOLU emissions (livestock and crop production and LULUCF together; categories b1 and b2 in Table 2) is then 18% of total global emissions, but emissions beyond the farm gate in non-AFOLU sectors (categories b3–b5) amount to 11% of total global emissions – high enough to be addressed with the same urgency as farm gate emissions.

8 In fact, the IPCC (Riahi et al. 2022) gives this value for 2019, but the annual deviation would be only 1.3%, which seems negligible given the large uncertainties surrounding these data.

9 Food system emissions are given as 32% (range 23%–42%) of global total emissions in Babiker et al. (2022).

Table 2. IPCC global food system emissions estimates (2018)

Sector category	Emissions ($GtCO_2$-eq per year)	Emissions: Lower ($GtCO_2$-eq per year)	Emissions: Upper ($GtCO_2$-eq per year)
Total anthropogenic emissions (a)	59	53	65
Total global food system emissions (b)	17	13	23
• Agriculture (livestock and crop production) (b1)	6.3	2.6	11.9
• LULUCF (b2)	4	2.1	5.9
• Food system energy use (b3)	3.9	3.6	4.4
• Food system waste management (b4)	1.7	0.9	2.6
• Food system IPPU (b5)	0.9	0.6	1.1

Sources: Total anthropogenic emissions adopted from IPCC AR6 (Riahi et al. 2022); food system emissions adopted from Babiker et al. (2022).

Discussion

Global food system GHG emissions have been estimated at around 16, 17 and 18 $GtCO_2eq/yr$, according to FAOSTAT, IPCC and EDGAR Food data, respectively. These values are surprisingly consistent given the large methodological differences and the overall uncertainty over food system emissions data (Table 2). For comparison, emissions in the AFOLU sector (i.e., land-use changes and farm gate emissions), while considered in the literature as well understood and well quantified, are still associated with very high uncertainties in the range of 30% to 50% (Smith et al. 2014; Mbow et al. 2019; Pingault and Martius 2023). Table 2 (adapted from Babiker et al. 2022) presents an even greater level of uncertainty for agricultural emissions.

These uncertainties are due to a limited understanding of the complex biophysical and biological processes, spatial and temporal dynamics and feedback loops involved in land-climate interactions. But they are also due to a lack of data, particularly for non-farm emissions (Niles et al. 2018; Mbow et al. 2019; Pingault and Martius 2023; Ruggeri Laderchi et al. 2024). Collecting detailed data on agrifood system emissions and mitigation potential – disaggregated by greenhouse gas, source of emission or geographical scale – is challenging because of: (i) the complexity of biological and biophysical processes at stake, as well as their complex, often non-linear, spatial and temporal dynamics and feedback loops; (ii) the wide diversity of ecosystems, geoclimatic zones, farming and food systems; and (iii) the multiplicity of actors involved in agriculture and food systems, many of whom are smallholders (Pingault and Martius 2023). The lack of strong data and evidence base is particularly concerning for some sources of emissions, such as food loss and waste (e.g., HLPE 2014; Axmann et al. 2024a, 2024b, 2024c, 2024d). This limits the design of reliable policies to implement effective action.

In sectors like fisheries and aquaculture – while their emissions appear to be relatively small[10] compared with agriculture – the lack of consistent data and the absence of coverage in IPCC methodological guidelines complicate the integration of these sectors into national GHG inventories and mitigation strategies. As a result, their emissions are often overlooked or underestimated (Barange et al. 2018; Mbow et al. 2019; Pingault and Martius 2023; Martius et al. 2023c).

Another concern lies in the trade-offs between development objectives. Specifically, there are fears that reducing food system emissions could threaten food security and nutrition, especially for vulnerable populations, as discussed at recent conferences of the parties to the United Nations Framework Convention on Climate Change (UNFCCC). However, given the significant size of food system emissions and the wide-reaching impacts of climate change on food production, this legitimate concern should not prevent the exploration of sustainable mitigation pathways in land use and food systems. Pursuing holistic, low-emission, resilient, fair and sustainable food systems is essential for a sustainable future. Neglecting food system emissions could jeopardize future food security, as climate change heavily impacts ecosystems that support food production.

Moreover, high agricultural emissions may signal inefficiencies in farming systems and food value chains. An integrated approach that addresses these inefficiencies can align climate-change mitigation and adaptation, which are two development goals that – while closely linked – have historically been treated separately under the UNFCCC. Prioritizing cost-effective, viable actions that offer multiple benefits is essential for sustainable development. To support low-emission development in line with the Paris Agreement – without compromising food security, nutrition or livelihoods – there is a need for more data, knowledge and tools that are tailored to national contexts (Martius et al. 2023a).

Strategic considerations

Building on this discussion, an effective strategy for reducing emissions in the global food system involves a holistic consideration of all emission sources along the entire food-supply chain. This strategy should prioritize

10 Although representing 17.4% of all animal proteins in the average human diet (FAOSTAT FBS), fisheries and aquaculture account for about 0.58 $GtCO_2eq$ per year globally (Barange et al. 2018), which is less than 10% of global agricultural GHG emissions and just 1% of global net GHG anthropogenic emissions.

	Percentage of total anthropogenic (mean)	Percentage of total anthropogenic: Lower (a)	Percentage of total anthropogenic: Upper (a)	Percentage of total food system (mean)	Percent of total food system: Lower (b)	Percent of total food system: Upper (b)
	100	100	100			
	28.8	24.5	35.4	100	100	
	10.7	4.9	18.3	37.1	20	51.7
	6.8	4	9.1	23.5	16.2	25.7
	6.6	6.8	6.8	22.9	27.7	19.1
	2.9	1.7	4	10	6.9	11.3
	1.5	1.1	1.7	5.3	4.6	4.8

emissions reduction pathways that effectively contribute to the 1.5°C climate goal by applying the following key criteria to guide decision making and prioritization:

- Emission size: Focus not only on major emission sources, like "net forest conversion" and "enteric fermentation," which are significant but difficult to mitigate. Also consider smaller sources, such as "agrifood system waste disposal," "household food consumption," and "food transport."[11] Taken together, these smaller emission sources can have an impact equivalent to larger emission sources, yet they may be easier to reduce by using existing, affordable technologies.
- Costs of emissions reduction: Use marginal abatement cost curves (MACCs) to evaluate the costs of reducing specific emissions and to identify cost-effective strategies (Li et al. 2024). These costs vary widely depending on local climate, ecosystems, socioeconomic conditions, farming systems and technologies. Developing reliable MACCs may require significant data collection, research and modelling across different biomes and socioeconomic contexts. Estimating these abatement costs is key to assessing feasibility.
- Feasibility and desirability: Assess the feasibility of alternative technologies and mitigation options for emissions reduction.[12] Not all desirable mitigation options are also highly feasible. The feasibility will increase if it brings multiple co-benefits for sustainable development and is technically, politically and socially viable – besides being a good economic solution. Factors such as political and institutional support, public acceptance, resistance to change, social norms or cultural beliefs necessitate a nuanced approach to policy and intervention design.

A concurrent consideration of these criteria can help decision makers to identify high-priority areas for interventions based on the specific context of their country or region.

Conclusion and recommendations

The global food system is responsible for one-third of total global net anthropogenic emissions. By size, this is on par with the emissions of China – which emits more GHGs than any other country (31% of global emissions in 2020) – and significantly higher than those of the United States, which ranks second (13.5%) on the list of major emitting nations (see FAOSTAT).[13] Thus, reducing food system emissions should be a key action in mitigation strategies. The large contribution from livestock digestion processes underscores the need for innovative solutions in animal agriculture, such as dietary changes or methane-reducing technologies. While AFOLU emissions still form the bulk of food system emissions, the share of non-AFOLU emissions is increasing and even becoming preponderant in industrialized countries.

Emission sources are arbitrary categories. Often, in the datasets, large sources refer to aggregated categories, such as livestock, while emissions beyond the farm gate are disaggregated, making them look smaller. When aggregated, smaller emission sources – including food system waste disposal, energy use and transport – cumulatively represent a significant share (33%) of food system emissions, according to FAOSTAT (Table 1). When looking at the costs, viability and political economy of climate action, addressing multiple smaller emission sources could be as impactful as targeting emission sources that have larger mitigation potential but are harder to address (such as livestock emissions). This may offer more practical pathways for emissions reductions, leading to faster, cheaper and easier progress.

11 The terms quoted here in quotation marks follow FAOSTAT terminology.

12 A systematic and comprehensive Opportunity Assessment Framework (OAF) is under development (Pingault and Martius, forthcoming) to expand these strategic considerations and allow the ranking of alternative mitigation options according to their level of opportunity (i.e., desirability and feasibility). The OAF includes 23 indicators covering the six IPCC dimensions of feasibility (geophysical, environmental-ecological, technological, economic, sociocultural and institutional; IPCC 2022). Using the OAF could help raise the ambition of NDCs and climate policies by identifying and prioritizing 'low-hanging fruits', meaning viable mitigation options that have highly transformative potential, are easy to implement quickly and are best adapted to local circumstances, priorities and needs.

13 See also: https://www.globalcarbonproject.org/carbonbudget/archive/2021/GCP_CarbonBudget_2021.pdf

The sectoral approach (distinguishing the four sectors of energy; IPPU; AFOLU and waste), followed by the IPCC and by parties to the UNFCCC in their NDCs, makes it more difficult to identify and address cross-sectoral issues, synergies and trade-offs. Tubiello et al. (2021; Figure 1) compare the sector mapping of emission sources in IPCC inventories with FAOSTAT categories, showing that the categories in each system are not congruent.[14] As a result, analysing food system emissions and climate policies at both national and global levels is challenging because the food system information is not easily extracted from GHG inventories. This is further complicated by insufficient data on activities; the lack of specific emissions factors; the lack of an integrated overview of food system emissions; and inadequate systematic data collection across food value chains. Hence, unsurprisingly, national food systems are still not adequately reflected in many NDCs despite their critical importance for climate change mitigation (GAFF 2022). As food systems span across the four IPCC sectors, we need an integrated, cross-sectoral, holistic and comprehensive approach to efficiently reduce GHG emissions across food value chains while ensuring food security, nutrition, poverty reduction and sustainable development (Pingault and Martius 2023). This involves gathering detailed and disaggregated data, as well as integrating sustainable practices into policy frameworks, and leads to the following recommendations:

- Holistic and critical examination: Food system emissions data should be examined both holistically and critically to identify hotspots and opportunities for emissions reduction using available technologies and minimal investment.
- Detailed and disaggregated data: There is a need for more detailed and disaggregated data on food system emissions by gas, source of emissions, sector, region and part of the value chain to support informed decision making. Data collection should be improved on targeted sectors in the food system to facilitate the transformation to a low-emission food system. Various databases should be used complementarily to reduce gaps and discrepancies in data, leveraging their strengths in providing quantitative and improved data on global food system emissions.
- Policy integration: Policies that address food system emissions more holistically should be developed and implemented. This, in part, will require a focus on emissions across the usual NDC categories to identify large emission sources in this system, as well as suitable, highly viable entry points for climate action.

14 GHG inventories and the FAO categories are hard to reconcile because (1) "LULUCF" in GHG inventories, without "drained organic soils," is congruent to FAO's "land use change" category; (2) "agriculture" plus "drained organic soils" from LULUCF and "on-farm energy use" from "energy and IPPU" corresponds to FAO's "farm gate" emissions. "Energy and IPPU" and "waste" together, minus "on-farm energy use," correspond to "pre- and post-production" in FAO.

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