ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

PAPER • OPEN ACCESS

Harmonizing food systems emissions accounting for more effective climate action

To cite this article: Kevin Karl *et al* 2025 *Environ. Res.: Food Syst.* **2** 015001

IOP Publishing Environ. Res.: Food Syst. 2 (2025) 015001 https://doi.org/10.1088/2976-601X/ad8fb3

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

CrossMark

OPEN ACCESS

RECEIVED
16 May 2024

REVISED
3 October 2024

ACCEPTED FOR PUBLICATION
7 November 2024

PUBLISHED
25 November 2024

PAPER

Harmonizing food systems emissions accounting for more effective climate action

Kevin Karl[1,2,19,*], **Francesco N Tubiello**[3], **Monica Crippa**[4,5], **Joseph Poore**[6], **Matthew N Hayek**[7], **Philippe Benoit**[8], **Minpeng Chen**[9], **Marc Corbeels**[10,11,12], **Alessandro Flammini**[3,13], **Sarah Garland**[14], **Adrian Leip**[15], **Shelby C McClelland**[7], **Erik Mencos Contreras**[1,2], **David Sandalow**[16], **Roberta Quadrelli**[17], **Tek B Sapkota**[18] **and Cynthia Rosenzweig**[1,2]

1 Columbia Climate School, Columbia University, New York, NY 10025, United States of America
2 NASA Goddard Institute for Space Studies, New York, NY 10025, United States of America
3 Food and Agriculture Organization of the United Nations, Rome, Italy
4 European Commission, Joint Research Centre (JRC), Ispra, Italy
5 Unisystems S.A., Milan, Italy
6 Department of Biology, University of Oxford, Oxford, United Kingdom
7 Department of Environmental Studies, New York University, New York, NY, United States of America
8 Global Infrastructure Advisory Services 2050, Washington, DC, United States of America
9 School of Agricultural Economics and Rural Development, Renmin University of China, Beijing 100872, People's Republic of China
10 International Institute of Tropical Agriculture (IITA), PO Box 30772, Nairobi 00100, Kenya
11 CIRAD, UPR AIDA, Nairobi, Kenya
12 AIDA, University Montpellier, CIRAD, Montpellier, France
13 Department of Environment, United Nations Industrial Development Organization, Vienna, Austria
14 Triple Helix Institute for Agriculture, Climate and Society, New York, NY, United States of America
15 European Commission, DG Research & Innovation, Bioeconomy and Food Systems Unit, Brussels, Belgium
16 Center on Global Energy Policy, School of International and Public Affairs, Columbia University, New York, NY, United States of America
17 International Energy Agency, Paris, France
18 International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico
19 Indicates co-lead authors.
* Author to whom any correspondence should be addressed.

E-mail: kevin.karl@columbia.edu

Keywords: food systems, climate change, IPCC, mitigation, GHG emissions, GHG accounting

Abstract

Food systems—encompassing activities in food production, land-use change, supply chains and waste management—contribute significantly to climate change. Recent estimates indicate that food systems produce over 30% of annual anthropogenic greenhouse gas (GHG) emissions (about 20% of CO_2, 50% of CH_4, and 75% of N_2O), with the Intergovernmental Panel on Climate Change (IPCC) estimating a notably broad range of 23%–42% of global GHG emissions. This paper synthesizes current research on the contributions of food systems to climate change, highlights challenges in quantifying their impact and proposes a harmonized accounting framework for more effective climate action. We recommend that an expert committee aligned with the IPCC develop guidance for food systems emissions accounting in four key areas, including: (1) defining system boundaries and nomenclature; (2) developing protocols to allocate broader sectoral emissions to food systems; (3) prioritizing critical areas for research into activity data and emissions factors; and (4) developing a balanced framework for evaluating the impact of mitigation interventions in light of other food systems imperatives. The committee should be integrated into two key international policy processes—the United Nations Framework Convention on Climate Change and the United Nations Food Systems Summit—to support coordinated action towards global net-zero goals. Guidance from the committee could significantly improve the ability of governments, companies, and researchers to estimate, report, monitor and ultimately reduce the climate impacts of food systems.

1. Introduction

Food systems encompass a continuum of interconnected activities, including manufacturing of farm inputs, crop and livestock production, aquaculture and fisheries, land-use change processes, supply chain activities (including food processing, packaging, transportation, and retail), household consumption, and the disposal of food systems waste (Rosenzweig *et al* 2021, Tubiello *et al* 2022a) (figure 1). They contribute a substantial proportion of global anthropogenic greenhouse gas (GHG) emissions (Mbow *et al* 2019). Recently available country-level estimates suggest that food systems currently contribute over 30% of annual GHG emissions (Crippa *et al* 2021, Tubiello *et al* 2021a). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) presented a wider range of 23%–42%, underscoring significant uncertainty, due both to incomplete knowledge and the adoption of widely different methodological approaches (Babiker *et al* 2022).

Food systems emit a variety of GHG. In 2020, they were estimated to account for 21% of total anthropogenic CO_2 emissions, primarily from land-use change and energy consumption in food supply chains and households (FAO 2022). They were also estimated to generate 53% of global anthropogenic CH_4 emissions in 2020, largely from enteric fermentation from ruminant livestock and from solid food waste disposal, as well as 78% of global N_2O emissions, mainly from fertilizer application and manure management (FAO 2022). Furthermore, food system cold chains, primarily in food retail, were estimated to contribute 26% of global fluorinated gas emissions (in CO_2-equivalents) (FAO 2022).

Despite the magnitude and diversity of GHG emissions from food systems, there are no internationally coordinated initiatives within the scientific community aimed at standardizing system boundaries, harmonizing methodological approaches, and formulating transparent protocols for quantifying GHG emissions and removals across all food system activities. This gap can lead to divergent assessments of where to target mitigation interventions, as well as confusion about how to assess their efficacy and monitor their impact over time in line with stated net-zero goals (Deconinck *et al* 2023).

This paper explores challenges in quantifying emissions from food systems and proposes pathways towards a comprehensive accounting framework. In particular, we argue that an internationally coordinated process should advance scientific consensus in four key areas (figure 2):

1. Definitions of food systems emissions boundaries and nomenclature
2. Protocols to allocate sectoral emissions to food systems
3. Prioritization of research areas to enhance food systems activity data and emissions factors
4. Balanced framework for estimating the full impact of food systems mitigation interventions

2. Defining system boundaries and nomenclature

Global emissions from food systems have been characterized and estimated using life cycle assessment (LCA) approaches (Poore and Nemecek 2018, Gephart *et al* 2021), multi-region input–output (MRIO) approaches (Li *et al* 2022), and national inventory-based (NIB) approaches (Crippa *et al* 2021, Tubiello 2021b), among other methods. LCA approaches compile case studies of emissions from each stage of a commodity's supply chain, often adopting a 'cradle to grave' approach (Hellweg and Milà I Canals 2014). NIB approaches utilize data from National GHG Inventories (NGHGIs), which were developed to facilitate international reporting and compliance as part of the United Nations Framework Convention on Climate Change (UNFCCC) (Pulles 2017). MRIO methods analyze flows across economic sectors and regions, and can track the environmental impacts of supply chains using trade and industrial data, enabling a consumption-based accounting approach (Kanemoto *et al* 2012).

While each of these approaches can yield valuable emissions estimates tailored to specific informational needs, they sometimes result in conflicting estimates, which can obfuscate rather than clarify our understanding of food system emissions. For example, recent scientific discourse about the term 'food miles' highlights how similar terminology can be utilized to communicate different perspectives on the climate impacts of food transportation, depending on the methodological approach taken and the definition of the term itself (Tubiello *et al* 2022b). Much of the debate revolves around the issue of system boundaries, such as whether the movement of all inputs into food systems (e.g. fertilizer and pesticides) should count as 'food systems transportation', rather than just the transportation of food. The lack of standardized nomenclature leads to substantially different estimates for the climate impacts of global food transportation (table 1).

Significant progress has been made to develop and standardize core food systems concepts in support of international policy action. The United Nations Food Systems Summit laid important conceptual foundations by defining the intersection of food systems with ecological and climate systems, science and innovation systems, economic and governance systems and health systems (von Braun *et al* 2021). The IPCC

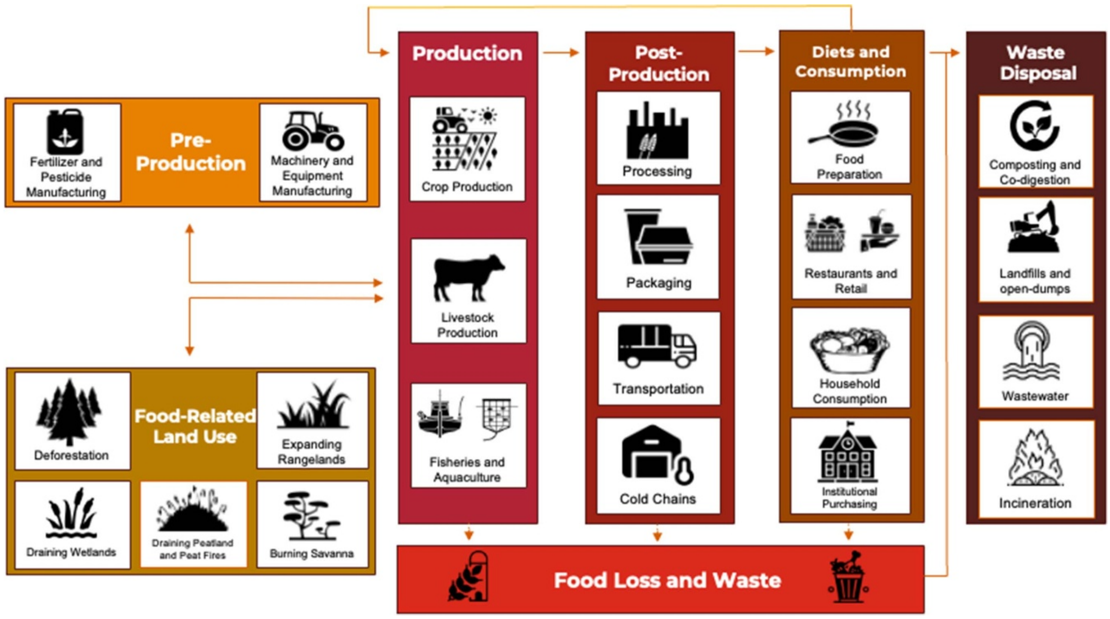

Figure 1. GHG emissions sources in the food system, adapted from Rosenzweig *et al* 2021. Icons for various system components downloaded from The Noun Project. CC BY 3.0. From top–left to bottom–right: Fertilizer by Syaiful Amri,Tractor by Olivier, Forest by Nesdon Booth, Wetland by Iconathon, Moss by Laymik, Thick Grass by Hamish, Savanna by Hamish, Farming by ProSymbols, Cow by Alexandr Lavreniuk, Boat by Amethyst Studio, Aquaculutre by Angelo Troiano, Grains Silo by Ben Davis, GMO by Stephanie Wauters, Food Conatiner by dDara, Tranport by Prianka, Temperature by Andrejs Kirma, Cooking by Erik Arndt, Grocery by Iconixar, Fast Food by Kristina Margaryan, School Building by Siipkan Collective, Waste by Priyanka, Compostable by Luca Reghellin, Excavator on Landfill by Peter van Drie, Waste water by Mavadee, Incineration by Eucalyp. Reproduced from Cynthia Rosenzweig *et al* (2021). Copyright The Author(s). Published Ltd CC BY 4.0.

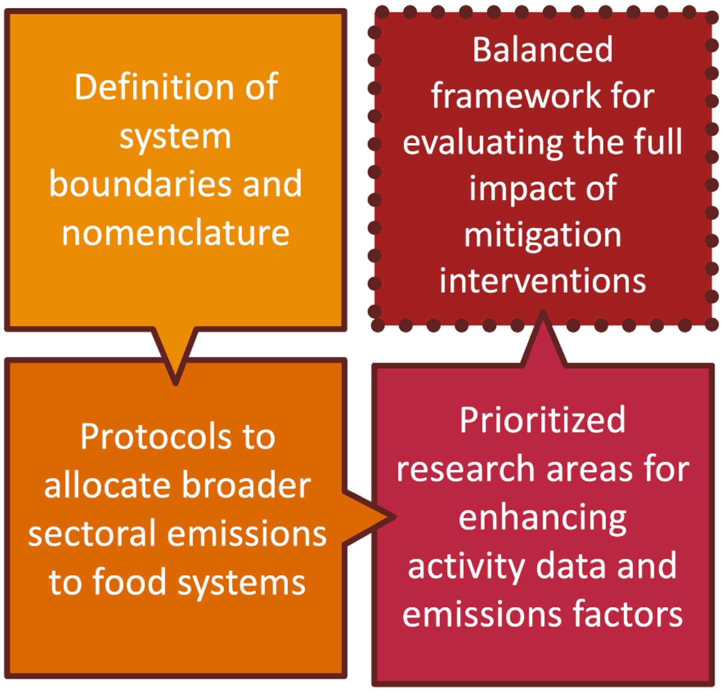

Figure 2. Four areas where expert collaboration and consensus are required to advance effective emissions accounting in food systems.

Sixth Assessment Report summarized recent food systems emissions estimates (Babiker *et al* 2022), reporting on commodity-specific GHG intensities from LCA meta-analysis as well as emissions estimates derived from NIB approaches. However, neither of these processes included comprehensive deliberation on which activities should be included in food systems emissions accounting. We build on these foundational efforts by offering insights into how distinct methodological approaches and disparate system boundary definitions can be harmonized to advance consistent estimates of GHG emissions from food systems.

GHG emissions accounting boundaries in agriculture and related land-use change (‘production’) are generally well-established (IPCC 2006, 2019). However, existing frameworks differ with respect to the activities they include in ‘pre-production’ estimates (e.g. emissions from fertilizer manufacturing) and ‘post-production’ estimates (e.g. emissions from food systems waste disposal). For example, some approaches include all upstream emissions from oil and gas supply chains, including fugitive emissions, in there pre-production accounting boundaries, while others do not (Tubiello *et al* 2022b). Similarly, some include emissions from domestic wastewater in their post-production accounting boundaries, while others forego it entirely (Tubiello 2021b). There are also numerous inconsistencies related to aggregating and appointing emissions from various activities into broader food system components, which can complicate comparative evaluations (table 2).

Furthermore, some studies have utilized ‘agrifood systems’ (instead of ‘food systems’) as an analytical lens, emphasizing the broader systemic relationships that tie food and non-food activities together across agriculture, forestry and fisheries. Such categorization includes the production of bioenergy, forestry products, and natural fiber (Miranda *et al* 2021) Here we emphasize solely food-specific activities, recognizing that the nature of available data at the macroscale does not easily allow for the distinction between food-related and non-food-related emissions estimates in many cases (Flammini *et al* 2023a, 2023b).

To clarify system boundaries, we propose that an internationally coordinated process, involving an expert committee, provide clear guidance on which activities should be included and excluded under different emissions accounting approaches. This process should be aligned with established international processes (i.e. UNFSS) in terms of systems boundaries, and the UNFCCC and IPCC in terms of GHG accounting rules for national reporting. While there may not be a single ‘right’ answer to these complex boundary questions, developing a shared and transparent understanding is vital to develop comparable assessments of best practices in food systems emissions accounting.

3. Intersectoral allocation of emissions to food systems activities

Most emission factors used to quantify food systems emissions in the scientific literature are based on IPCC Guidelines for NGHGIs (IPCC 2006, 2019) and LCA studies (Poore and Nemecek 2018, GHG Protocol 2024). While the frameworks within which they are derived are methodologically distinct—the former follows national boundaries and generic processes, while the latter focuses more on tracking commodities along supply chains—they are not mutually exclusive; many LCA tools already utilize IPCC emission factors, and many IPCC co-efficients are based on collections of LCA studies.

The IPCC reporting guidelines do not focus on ‘food systems’ as a distinct category because food systems are a conceptual framework that cuts across multiple IPCC (and International Standard Industrial Classification, ISIC) sectors. When utilizing existing IPCC methods, emissions related to food systems are reported by countries to the UNFCCC separately in five discrete sectors: Energy; Industrial Processes and Product Use (IPPU); agriculture; land use, land use change and forestry (LULUCF; the latter grouped by the 2006 IPCC Guidelines into the Agriculture, Forestry and Other Land Use or AFOLU category); and waste (figure 3). However, many food systems activities do not fit neatly into these sectoral categories, such as irrigation, where on-farm energy use and groundwater degassing would be represented in energy and AFOLU categories, respectively (Driscoll *et al* 2024, Qin *et al* 2024). While IPCC Agriculture processes are well characterized and directly attributed to food systems activities, the fraction of LULUCF and especially energy, IPPU, and waste emissions attributable to food systems is more difficult to estimate, and protocols to guide such estimations are relatively underdeveloped. Existing data structures and classification systems, such as the ISIC system, are simply not designed to organize information on cross-sectoral processes.

One challenge in harmonizing approaches is finding the right convergence point between them. Theoretically, a meta-analytical LCA approach can develop a plausible range of emissions factors for distinct processes across a commodity’s supply chain, based on production patterns and logistical arrangements in a given context (e.g. Poore and Nemecek 2018). These emissions factors can be applied to NIB activity data at the country level—ideally weighted spatially and by production type and volume—which could be used to generate bottom–up estimates of commodity-specific emissions at the national level.

These emissions estimates could also be disaggregated by various steps in the supply chain, utilizing coefficients from LCA studies, and applied to NIB data to estimate the proportion of sectoral emissions attributable to food systems (here referred to as ‘food shares’). Food shares can be used to provide emissions estimates for countries where comprehensive LCA data are not explicitly available, but where NIB data are (Tubiello 2021b). If NIB data are not available at the necessary resolution (e.g. at the sub-sector or individual commodity level), protocols to disaggregate sectoral emissions by commodity type could be developed by

Table 1. Approaches to estimating GHG emissions associated with global food transport. Adapted from Tubiello *et al* (2022b).

Study	Method	Strengths	Limitations	Scope	Gt CO_2eq yr^{-1}	Reference Year
Li *et al* (2022)	Multi-region input–output tables	Utilizes industry data sources. Enables consumption based accounting methods and cross-border analysis.	High uncertainties associated with primary data.	Transport of food and all food system inputs (farm machinery, fertilizers etc)	**3.0**	**2017**
				Transport of food only	**1.4**	
Crippa *et al* (2021) Tubiello *et al* (2022a)	National inventory-based Accounting (food share of NGHGIs)	Utilizes national statistical data that aligns with international accounting structures and processes.	Does not provide for consumption-based accounting. Food shares carry high uncertainties.	Transport of food only	**0.5–0.9**	**2017**

Table 2. Overview of pre- and post-agricultural production emission estimates from select studies (Gt CO_2eq yr^{-1}) from a non-exhaustive list of food systems components.

Food systems component	FAO (2011)	Vermeulen *et al* (2012)	Poore and Nemecek (2018)	EDGAR-FOOD v6 (2021)	FAOSTAT (2023)	Li *et al* (2022)
Reference year(s)	Mid-2000s	2004–2007	2009–2011	2017	2017	2017
Pesticide manufacturing	—	—	—	—	0.1	—
Fertilizers manufacturing	—	0.4	—	—	0.4	—
Cold chain (f-gas emissions from retail, processing, transport and consumption)	—	—	—	0.5	0.4	0.3
Household consumption—energy	1.2	0.2	—	0.5	1.0	1.5 ([a]including upstream fuel supply chains)
Retail—Energy	2.1 ([a]incl. machinery production)	0.7	0.4	0.3	0.4	
Processing—Energy		0.2	0.6	0.6	0.6	
Packaging—Energy		0.4	0.6	1.0	0.3	
Transport—Energy			0.8	0.9	0.5	3.0
Waste Disposal/Management	—	0.1	—	1.6	1.2	0.2
Total Pre- and Post-production emissions (Excluding LUC)	**3.3**	**2.0**	**2.4**	**5.4**	**4.9**	**5.0**

[a] Notes examples of where data are not comparable across approaches owing to a lack of standardized emissions accounting boundaries.

utilizing regionally-specific coefficients derived from LCA studies. MRIO methods could be applied to either commodity-based estimates or sectorally-derived estimates to track commodity-specific flows within and across countries, providing key insights into mitigation interventions targeted at consumers in addition to producers.

While promising in theory, most statistical agencies do not collect and disseminate activity data that are disaggregated at the commodity level, or even at the level of food itself. For example, food transportation as a percentage of total transportation is itself difficult to ascertain, and beef transportation as a percentage of food transportation is even more challenging. Further research and data are therefore required to accurately apportion sectoral emissions to food system processes at relevant scales.

Other systems, such as buildings, present similar challenges in emissions accounting (Röck *et al* 2020), and hence can offer valuable insights for protocols to estimate emissions from food systems. Emissions from buildings are generally categorized as either 'embodied' (i.e. indirect emissions from the production and life-cycle of energy and materials used to construct buildings), or 'operational' (i.e. direct emissions from energy use in a completed building) (Röck *et al* 2020). Operational emissions data are more readily available, and are often directly collected and reported by statistical agencies. Embodied emissions data, on the other hand, are embedded within the statistics of a variety of industrial processes (e.g. steel and concrete manufacturing and supply chains). To better characterize embodied emissions in buildings, researchers have conducted and analyzed sets of case studies, based on the LCA approach, with an eye towards mitigation opportunities (Birgisdottir *et al* 2017, Chastas *et al* 2018, Rasmussen *et al* 2018). Data produced in such studies yielded estimates of the share of embodied emissions within total building emissions for different building types and geographical contexts. These operational emissions shares facilitated emissions estimates at larger scales. (Chastas *et al* 2018).

Recently published food systems emissions datasets represent the current state-of-the-art in estimating similarly ascertained coefficients (i.e. food shares) (Tubiello 2021b). Despite the practicality the food share approach within NIB frameworks, comprehensive knowledge of time-dependent and context-specific food shares remain constrained by a lack of data and research attention (figure 3). Collecting relevant activity data at local and national levels would preclude the need for this apportioning approach, however, this would require significant additional efforts to adapt existing national data collection and inventory methods. Therefore, improving methods to estimate allocation fractions of emissions from sectors to food systems processes is one of the most expedient options the research community possesses to advance knowledge in the field.

NGHGI Sector	Food Systems Component	GHG				Food Systems Apportioning Required
		CH_4	N_2O	CO_2	F-Gas	
AFOLU	Net Forest Conversion	x	x	x		x
	Tropical Forest Fires	x	x	x		x
	Peat Fires	x		x		x
	Drained Organic Soils	x		x		x
	Burning - Crop residues	x	x			x
	Burning - Savanna	x	x			x
	Crop Residues		x			x
	Drained Organic Soils		x			x
	Enteric Fermentation	x				
	Manure Management	x	x			
	Manure Applied to Soils		x			
	Manure Left on Pasture		x			
	Rice Cultivation	x				
	Fisheries & Aquaculture	x	x	x		
	Synthetic Fertilizers		x			x
ENERGY	On-farm Energy Use	x	x	x		x
	Transport	x	x	x		x
	Fertilizer Manufacturing	x	x	x		x
	Pesticides Manufacturing	x	x	x		x
	Equipment Manufacturing	x	x	x		x
	Processing	x	x	x		x
	Packaging	x	x	x		x
	Retail					x
	Restaurant and Food Service	x	x	x		
	Household Consumption	x	x	x		x
IPPU	Cold Chain – Refrigeration	x	x	x	x	x
WASTE	Solid Waste	x				x
	Incineration			x		x
	Industrial Wastewater	x	x			x
	Domestic Wastewater	x	x			x

Figure 3. Examples of Food System Components mapped to National Greenhouse Gas Inventory (NGHGI) Categories. Reproduced from Francesco N Tubiello *et al* 2021a. Copyright The Author(s). Published Ltd CC BY 4.0.

Despite high uncertainties associated with allocation methods—due both to sparse observational data and high spatial and temporal heterogeneity—there are clear opportunities to reduce existing uncertainties and develop a shared understanding of the most meaningful sources of intersectoral food systems emissions. Here, an internationally coordinated expert committee can develop apportioning protocols and make suggestions for voluntary refinements to existing statistical systems (e.g. for food-systems-specific data collection). Such protocols could be of tremendous aid to public and private sector decision-makers charged with tabulating components of food system activities that are entangled with other sectoral inventories.

4. Prioritizing research areas to enhance food systems activity data and emissions factors

Emissions factors for activities in agriculture and land use are generally available through the IPCC AFOLU guidelines (IPCC 2006, 2019). However, they are sorely lacking for pre- and post-production activities (Tubiello *et al* 2021a). While providing comprehensive guidance on emissions factors for every food-related activity may not be practical (or cost-effective), an expert committee could help determine where further research and statistical resources would best be targeted to inform emissions estimates in high impact areas.

For example, GHG emissions from food retail, household consumption and food systems waste disposal are significant sources of global emissions (table 2), and each area could benefit from improved activity data and expert guidance on emissions factors. In the case of emissions from food activities in households, better activity data are required to improve estimates of how much non-renewable fuelwood is used for cooking in Africa and Asia (Flammini *et al* 2023a). In the case of food waste management, the availability of more climate-specific factors for determining the decay rate of organic materials, such as food waste, was shown to significantly improve estimates of methane emissions from landfills (Wang *et al* 2024). For estimates of emissions from food cold chains, improved activity data to quantify and characterize refrigeration systems, as well as detailed emissions factors for fluorinated gas mixes stemming from those systems, are sorely needed to manage the potent impact of fluorinated gases on climate change (Flammini *et al* 2023b).

Even where more detailed guidance on emissions factors are attainable, such as through the IPCC AFOLU guidelines, many inventory tools utilize Tier 1 methods and default emission factors provided by the IPCC (IPCC 2006, 2019). Often this choice is dictated by the poor current availability of nationally relevant coefficients, whereas use of more granular data at finer temporal and spatial scales would facilitate a move to higher tiers. The Tier 1 approach, such as the use of a 1% emission factor for estimating N_2O emissions from nitrogen fertilizer use, has been shown to work well at coarse resolution (De Klein *et al* 2006, Stehfest and Bouwman 2006, Tubiello *et al* 2013, Caro *et al* 2014), despite, for example, the nonlinear relationship between N input and N_2O emissions observed at the farm level (McSwiney and Robertson 2005, Hoben *et al* 2011, Shcherbak *et al* 2014). Indeed, recent field studies suggest that N_2O emissions from fertilizer applications in low-input cropping systems may be significantly lower than the default IPCC emission factor, underscoring the need for more context-specific emissions factors for localized assessments (Shumba *et al* 2023). While more complex approaches could potentially improve localized estimates, the lack of firm observations at the country level and limited data availability often preclude their use. In the case of emissions accounting from pre- and post-production activities, Tier 1 level guidance could be of immense value in estimating and monitoring emissions from food systems.

An expert committee on food system emissions accounting could prioritize where better emissions factors and activity data are most urgently needed, and develop protocols for their use, aligning with the general framework IPCC guidance. For example, recent refinements to IPCC guidelines provided significant updates to default conditions for soil organic stocks that were specific to climate zones and soil classes (IPCC 2019). Similar efforts could be applied to food supply chain processes (e.g. food processing categories) at the Tier 1 level, along with guidance on transitioning to higher-tier methods to improve the accuracy of emissions estimates across diverse contexts. It is important to acknowledge that this work does not start from scratch; existing methodological approaches can serve as a solid foundation for Tier 1 methods (Tubiello 2021b). Further refinement and approval by the IPCC bureau would require close cooperation with countries to ensure the guidelines meet their needs and requirements.

5. Towards more effective and balanced mitigation interventions in food systems

Disparate methodological approaches may not only lead to divergent conclusions, but may foster confusion and inhibit accountability. For example, technical specifications of agricultural soil carbon sequestration models can lead to significantly different results, with varying implications for assessing the mitigation efficacy of the practice across a range of contexts (Nayak *et al* 2019). This inconsistency is particularly concerning in light of the recent boon of public policies and private initiatives that aim to incentivize soil carbon accumulation (Paul *et al* 2023). The lack of internationally coordinated standards has left emissions accounting framework development in the hands of many disconnected entities. This has increased the risk that carbon exchange markets shape mitigation activities rather than public environmental policies (Phelan *et al* 2024), and the risk that investments have little to no net impact on reducing GHG emissions when all sources and sinks are considered (Guenet *et al* 2020, Saifuddin *et al* 2024).

This knowledge gap has already led to a proliferation of carbon credit protocols related to agriculture and food systems, each with its own unique approach and threshold for acceptable levels of uncertainty (Oldfield *et al* 2022). As of May 2023, there have reportedly been at least 860 carbon market projects developed in India alone—at a value of $300 million—and 50% of the credits have been claimed/used with little to no tangible benefit demonstrated on the ground (Trishant and Krishnamurthy 2024). Effective soil carbon sequestration incentive structures require a system of baselining and rigorous measuring, monitoring, reporting, and verification procedures to ensure investments are providing sustained mitigation value, while avoiding issues associated with leakage, additionality, double counting, and tradeoffs with other agricultural emissions sources (Oldfield *et al* 2022, Don *et al* 2024).

Beyond bolstering accountability mechanisms for carbon markets, there is also a timely opportunity to develop baselining systems for rigorous evaluations of new mitigation technologies, including comparative assessments of multiple food system mitigation pathways at once. The case of agricultural fertilizers illustrates this point. The complete carbon footprint of fertilizer products encompasses mining and resource extraction, transportation of ingredients, significant energy inputs for the Haber–Bosch process, and further emissions that may stem from field application and resultant runoff (Tubiello 2021b). These activities contribute highly variable amounts of CO_2 and N_2O emissions, depending on the type of fertilizer produced and used, and how applications were managed. Some estimates of fertilizer GHGs are restricted to emissions from field applications alone, while others include the entire input supply chain. In the absence of standardization, the emissions reduction capacity of an intervention in the fertilizer space could be pitched to investors and consumers without clearly defining the scope of the fertilizer footprint being addressed. This could lead to bias, misrepresentation and greenwashing.

More accurate emissions accounting would also improve analyses that examine trade-offs between mitigation and adaptation goals in food systems. For example, the imperative to enhance system resilience and efficiency by reducing food waste could lead to increased emissions in food packaging (Babikar 2022). A recent study illustrates how integrating mitigation estimates with adaptation indicators can assess mitigation-adaptation co-benefits and trade-offs of various climate-smart agricultural practices (Rosenzweig C *et al* na). Extending beyond assessments in agricultural production, a thoughtful and integrated approach is required to examine the ripple effects that interventions in one component of the food supply chain can have across the entire system.

For example, expanding cold chain infrastructure could reduce post-harvest food loss and waste, which could in turn alleviate pressure to convert land to agricultural uses—a key source of food systems emissions (Kummu *et al* 2012). However, the expansion of cold chain infrastructure would increase energy consumption, which may further increase GHG emissions if based on fossil fuels (James and James 2010, Sims *et al* 2015). Similarly, promoting sustainable aquaculture practices could help meet the growing global demand for protein while reducing terrestrial methane emissions from ruminants and animal manure storage (Gephart *et al* 2021). Yet the expansion of aquaculture may lead to the decline of mangrove forests, jeopardizing the achievement of important biodiversity and carbon sequestration goals (Ahmed *et al* 2019, Costello *et al* 2020).

Recent global mitigation estimates underscore how a lack of data and research across the full suite of food systems activities can limit both the scope and type of mitigation interventions that are considered. For example, Costa *et al* (2022) do not examine the abatement potential of pre-production or post-production activities—such as fertilizers manufacturing, food cold chains, or food waste management—within their menu of food systems mitigation options. Other studies comprehensively evaluate emissions from food loss and waste management practices (Zhu *et al* 2023), but do not consider the upward pressure on emissions that could result from increased efficiency in food production and supply chains (Kuiper and Cui 2021). More research is needed to understand the systems-wide dynamics of mitigation interventions targeted at various stages of the food value chain.

While GHG emissions accounting structures are not themselves designed to directly assess the complex social, economic, and environmental consequences of mitigation strategies, expert guidance can indicate best practices for comprehensive evaluations of mitigation interventions in a food systems context. Such a framework could help ensure that researcher and policymakers balance the imperative to reduce GHG emissions from food systems with other core food systems imperatives, such as providing affordable, healthy and culturally-appropriate diets for all and protecting the livelihoods of those who rely on economic activities across food value chains (Herrero *et al* 2020, Hebinck *et al* 2021, Søndergaard *et al* 2023, Karl *et al* 2024). For example, interventions that encourage plant-based diets could significantly reduce emissions from agriculture and agricultural land-use change stemming from livestock production (Springmann *et al* 2018). But these environmental benefits may come at the expense of increasing near-term social risks, leading to trade-offs between mitigation efforts and the protection of livelihoods for communities that depend on animal agriculture (Rust *et al* 2020, Frehner *et al* 2022). An expert committee can provide guidance on the critical externalities to consider when evaluating a menu of food systems mitigation options, such as in food safety, food security, food justice, climate-resilience, nutrition and rural economic development.

6. Challenges in current frameworks and initiatives

To demonstrate the value of a harmonized approach, we illustrate several emerging efforts to quantify and track emissions from food systems, each with distinct advantages and challenges (table 3). Data-driven monitoring frameworks, such as the Food System Countdown Initiative (FSCI), provide a comprehensive and standardized way to track country-level progress across a series of food system indicators, including GHG emissions (Fanzo *et al* 2021). The GHG emissions data used in the FSCI are drawn from FAOSTAT statistics (Schneider *et al* 2023), consistent with the framework's requirement of readily available country data with global coverage and sufficiently long time series (Tubiello *et al* 2013). As previously discussed, the NIB approach utilized here may benefit in the future from the use of MRIO methods, which can help examine the impacts of trade dynamics across national boundaries and extend the analysis of where mitigation efforts should be focused.

The GHG Protocol Land Sector and Removals Guidelines, combined with the Science Based Target Initiative Forest, Land, and Agriculture (SBTi FLAG) Guidelines are defining system boundaries for which emissions can and cannot be included in the food and land sector for corporate GHG accounting. They are

Table 3. Challenges to existing frameworks and potential benefits of harmonized approaches.

Framework	Example methodological challenge	Harmonized approach could offer
Food System Countdown Initiative	NIB approach limits the ability to capture commodity-specific details and trade flows.	Standardized food system MRIO protocols to estimate flows of embodied emissions across national boundaries.
SBTi FLAG Guidelines	Lack of unified emissions factor datasets offered. Users can rely on bespoke corporate accounting methods with little standardization. Soil carbon accounting issues persist (e.g. additionality, permanence, leakage, tradeoffs with other GHG emissions).	Standardized dataset of localized emissions factors. Protocols to constrain corporate accounting methods. International standards for soil carbon sequestration accounting. Inclusion of non-CO_2 GHGs to evaluate emissions tradeoffs.
EU Environmental Footprint	Limited number of parameters used in emissions estimation models.	Resources and protocols to guide comprehensive emissions evaluations (e.g. through systems boundary definitions)
Mitigate+	Lack of data for supply chains tied to smallholder communities. Time and cost required to collect activity and emissions data across food system activities.	Resources to develop supply chain emissions factors in data-scarce environments. Protocol for mitigation potential quantification at various tiers of data availability.

used for corporate net zero commitments and could substantially determine where businesses place their carbon mitigation focus. For example, the guidelines include emissions related to the production of agricultural inputs in the land sector, which extends the focus of food companies' mitigation activities back down the supply chain. These guidelines are based on emissions factors that are either calculated by companies themselves, or based on a wide variety of GHG calculation methods and tools provided as resources to the companies (GHG Protocol 2024)· While these resources are highly valuable, there is an opportunity to further standardize emissions factors for calculating food system emissions, ideally at a localized level for different commodities and production systems. This would help to ensure consistency and comparability across various actors and sectors involved in emissions accounting. These guidelines will also clarify how removals (e.g. in soil carbon) can be quantified and reported, supporting greater transparency and accountability in this area.

The European Union (EU) Environmental Footprint program is defining life cycle GHG accounting protocols for specific products and organizations, alongside protocols for other environmental impact indicators (European Commission 2024). It defines system boundaries, characterization factors, allocation procedures, and states which emission models can be used to quantify each emission. However, the high level of model prescription comes at a cost: some models are heavily simplified and use few input parameters—e.g. N_2O emissions in crop production is estimated from fertilizer use and irrigation only, missing other important biophysical parameters—meaning the wrong levers may be focused on. A harmonized approach could offer resources and protocols to advance more comprehensive emissions models.

The CGIAR Initiative on Low-Emission Food Systems, known as Mitigate+, operates within Colombia, Kenya, Vietnam, and China, focusing on quantifying GHG emissions and mitigation potential from food system activities (CGIAR 2024). This initiative employs a bottom–up approach to quantifying emissions and mitigation potential so that mitigation efforts can be implemented by sector and by jurisdiction. While the primary aim is to utilize minimal and readily available data at the jurisdictional level, the absence of spatially disaggregated activity data presents a significant challenge. This highlights the persistent challenge of GHG emissions accounting in relatively understudied food supply chains. Consequently, the initiative has focused on generating such data to facilitate the bottom–up quantification of food system emissions in target countries. The provision of such data enables countries to quantify GHG emissions across their food systems, identify emission hotspots throughout the various stages of the food system, explore mitigation options across the entire system, and quantify the potential for mitigation and associated costs. Providing emissions factors for various activities of the food supply chain across geographical contexts—even at a Tier 1 level—would be a huge boon to such an initiative.

7. Conclusion

The urgent need to mitigate climate change requires well-designed programs and policies in support of internationally coordinated action. We highlight both the need, and opportunity, for an internationally coordinated scientific process to bring clarity and definition to food system emissions accounting structures. We recommend specific areas where an expert committee, aligned with the IPCC, can meaningfully advance scientific consensus on this important topic.

Specifically, the committee should focus on defining system boundaries for food systems emissions accounting and developing protocols for how to allocate a wide spectrum of cross-sectoral emissions to food systems. It should also identify key data gaps, where further research should be prioritized, and recommend a framework that ensures that mitigation efforts are designed in light of other food systems objectives.

We recommend that this expert committee be established within existing IPCC structures, such as the Task Force on NGHGIs. One key output of the committee could be a supplementary *Good Practice Guidance* report, containing a set of voluntary but standardized guidelines for more accurate and interoperable inventory accounting of food system GHG emissions. As IPCC guidelines already robustly cover the food systems components in agriculture, the focus of these guidelines should be on activities that produce GHGs in pre-production and post-production processes. Improved accounting for these activities can meaningfully contribute to system-wide mitigation analyses, such as in the realm of dietary choice and food loss and waste reduction. By building consensus on these critical issues, the scientific community can inform the design of effective carbon markets, and support the development of policies and incentives that will drive effective and balanced food systems transformation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgment

Support for this study to MCo and TBS was provided through the CGIAR initiative Mitigate+: Research for Low-Emission Food Systems, and through the contributions of all funders to the CGIAR Trust Fund. Cynthia Rosenzweig acknowledges support from the NASA Climate Impacts Core Project [WBS number 509496.02.80.01.03].

Author contributions

Originating ideation of many of these concepts came from F N T and C R. K K, S G, M N H, and S C M conceived of the original scope and structure of this paper. K K served as coordinating lead author. F N T, M Ch, M Co, S G, M N H, A L, S C M, J P, T B S and C R contributed substantial written components. F N T, E M C, C R and K K provided substantial editing throughout. P B, A F, MCr, D S and R Q provided key conceptual guidance.

The Agricultural Model Intercomparison and Improvement Project (AgMIP) played a crucial role in coordinating the work on this paper, which stemmed from a session at the AgMIP9 Global Workshop in 2023. The Food Climate Partnership (FCP) also contributed substantially to the development of this work.

Ethics declarations

The authors declare no competing interests.

Disclaimer

The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of the European Commission, the United Nations Industrial Development Organization, the Food and Agriculture Organization of the United Nations, or the National Aeronatics and Space Administration.

ORCID iDs

Kevin Karl https://orcid.org/0000-0002-8916-5578
Francesco N Tubiello https://orcid.org/0000-0003-4617-4690
Matthew N Hayek https://orcid.org/0000-0001-9792-4362
Minpeng Chen https://orcid.org/0000-0001-6159-6213
Sarah Garland https://orcid.org/0000-0003-2574-6629
Adrian Leip https://orcid.org/0000-0001-7616-5029

Erik Mencos Contreras https://orcid.org/0000-0002-4892-2368
Cynthia Rosenzweig https://orcid.org/0000-0002-7885-671X

References

Ahmed N, Thompson S and Glaser M 2019 Global aquaculture productivity, environmental sustainability, and climate change adaptability *Environ. Manage.* **63** 159–72

Babiker M *et al* 2022 Cross-sectoral perspectives *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) (https://doi.org/10.1017/9781009157926.005)

Birgisdottir H, Moncaster A, Wiberg A H, Chae C, Yokoyama K, Balouktsi M, Seo S, Oka T, Lützkendorf T and Malmqvist T 2017 IEA EBC annex 57 'evaluation of embodied energy and CO_2eq for building construction *Energy Build.* **154** 72–80

Caro D, Davis S J, Bastianoni S and Caldeira K 2014 Global and regional trends in greenhouse gas emissions from livestock *Clim. Change* **126** 203–16

CGIAR 2024 *Low-Emission Food Systems* (available at: www.cgiar.org/initiative/low-emission-food-systems/)

Chastas P, Theodosiou T, Kontoleon K J and Bikas D 2018 Normalising and assessing carbon emissions in the building sector: a review on the embodied CO_2 emissions of residential buildings *Build. Environ.* **130** 212–26

Costa C, Wollenberg E, Benitez M, Newman R, Gardner N and Bellone F 2022 Roadmap for achieving net-zero emissions in global food systems by 2050 *Sci. Rep.* **12** 15064

Costello C *et al* 2020 The future of food from the sea *Nature* **588** 95–100

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F N and Leip A 2021 Food systems are responsible for a third of global anthropogenic GHG emissions *Nat. Food* **2** 198–209

De Klein C *et al* 2006 N_2O emissions from managed soils, and CO_2 emissions from lime and urea application *2006 IPCC Guidelines for National Greenhouse Gas Inventories* vol 4 (IGES) pp 11.1–54

Deconinck K, Jansen M and Barisone C 2023 Fast and furious: the rise of environmental impact reporting in food systems *Eur. Rev. Agric. Econ.* **50** 1310–37

Don A, Seidel F, Leifeld J, Katterer T, Martin M, Pellerin S, Emde D, Seitz D and Chenu C 2024 Carbon sequestration in soils and climate change mitigation -definitions and pitfalls *Glob. Change Biol.* **30** e16983

Driscoll A W, Marston L T, Ogle S M, Planavsky N J, Siddik M A B, Spencer S, Zhang S and Mueller N D 2024 Hotspots of irrigation-related US greenhouse gas emissions from multiple sources *Nat. Water* **2** 837–47

European Commission 2024 Environmental footprint methods (available at: https://green-business.ec.europa.eu/environmental-footprint-methods_en) (Accessed 3 May 2024)

Fanzo J *et al* 2021 Viewpoint: rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals *Food Policy* **104** 102163

FAO 2011 Energy-smart food for people and climate (available at: www.fao.org/docrep/014/i2454e/i2454e00.pdf)

FAO 2022 Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000–2020 *FAOSTAT Analytical Brief Series No. 50* (available at: www.fao.org/3/cc2672en/cc2672en.pdf)

FAOSTAT 2023 Emissions from pre- and post-agricultural production (Accessed 9 May 2024) (available at: www.fao.org/faostat/en/#data/GPP)

Flammini A, Adzmir H, Karl K and Tubiello F N 2023a Quantifying greenhouse gas emissions from wood fuel use by households *Earth Syst. Sci. Data* **15** 2179–87

Flammini A, Karl K, Thacker D and Tubiello N F 2023b Methods for estimating greenhouse gas emissions from food systems. Part VI: fluorinated gas emissions *FAO Statistics Working Paper Series, No.* 35 10.4060/cc5403en

Frehner A, De Boer I, Muller A, Van Zanten H and Schader C 2022 Consumer strategies towards a more sustainable food system: insights from Switzerland *Am. J. Clin. Nutrit.* **115** 1039–47

Gephart J A *et al* 2021 Environmental performance of blue foods *Nature* **597** 360–5

GHG Protocol 2024 *Life Cycle Databases* (available at: https://ghgprotocol.org/life-cycle-databases)

Guenet B *et al* 2020 Can N_2O emissions offset the benefits from soil organic carbon storage? *Glob. Change Biol.* **21** 237–56

Hebinck A, Zurek M, Achterbosch T, Forkman B, Kuijsten A, Kuiper M, Nørrung B, van't Veer P and Leip A 2021 A sustainability compass for policy navigation to sustainable food systems *Glob. Food Secur.* **29** 100546

Hellweg S and Milà I Canals L 2014 Emerging approaches, challenges and opportunities in life cycle assessment *Science* **344** 1109–13

Herrero M *et al* 2020 Innovation can accelerate the transition towards a sustainable food system *Nat. Food* **1** 266–72

Hoben J P, Gehl R J, Millar N, Grace P R and Robertson G P 2011 Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US midwest *Glob. Change Biol.* **17** 1140–52

IPCC 2019 *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* edseds E Calvo Buendia, K Tanabe, A Kranjc, J Baasansuren, M Fukuda, S Ngarize, A Osako, Y Pyrozhenko, P Shermanau and S Federici (IPCC)

IPCC 2006 *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* ed H S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (IGES)

James S J and James C 2010 The food cold-chain and climate change *Food Res. Int.* **43** 1944–56

Kanemoto K, Lenzen M, Peters G P, Moran D D and Geschke A 2012 Frameworks for comparing emissions associated with production, consumption, and international trade *Environ. Sci. Technol.* **46** 172–9

Karl K, DeFries R, Baethgen W, Furtado M, Potent J, Leal E M, Contreras E M and Rosenzweig C 2024 Toward a holistic and data-driven framework to evaluate livestock-derived protein systems *One Earth* **7** 572–88

Kuiper M and Cui H D 2021 Using food loss reduction to reach food security and environmental objectives—a search for promising leverage points *Food Policy* **98** 101915

Kummu M, de Moel H, Porkka M, Siebert S, Varis O and Ward P J 2012 Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use *Sci. Total Environ.* **438** 477–89

Li M, Jia N, Lenzen M, Malik A, Wei L, Jin Y and Raubenheimer D 2022 Global food-miles account for nearly 20% of total food-systems emissions *Nat. Food* **3** 445–53

Mbow C *et al* 2019 *Food Security* GSFC-E-DAA-TN78913 (Special Report on Climate Change and Land)

McSwiney C P and Robertson G P 2005 Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system *Glob. Change Biol.* **11** 1712–9

Miranda B V, Monteiro G F A and Rodrigues V P 2021 Circular agri-food systems: a governance perspective for the analysis of sustainable agri-food value chains *Technol. Forecast. Soc. Change* **170** 120878
Nayak A K, Rahman M M, Naidu R, Dhal B, Swain C K, Nayak A D, Tripathi R, Shahid M, Islam M R and Pathak H 2019 Current and emerging methodologies for estimating carbon sequestration in agricultural soils: a review *Sci. Total Environ.* **665** 890–912
Oldfield E E, Eagle A J, Rubin R L, Rudek J, Sanderman J and Gordon D R 2022 Crediting agricultural soil carbon sequestration *Science* **375** 1222–5
Paul C, Bartkowski B, Dönmez C, Don A, Mayer S, Steffens M, Weigl S, Wiesmeier M, Wolf A and Helming K 2023 Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation? *J. Environ. Manage.* **330** 117142
Phelan L, Chapman P J and Ziv G 2024 The emerging global agricultural soil carbon market: the case for reconciling farmers' expectations with the demands of the market *Environ. Dev.* **49** 100941
Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92
Pulles T 2017 Did the UNFCCC review process improve the national GHG inventory submissions? *Carbon Manage.* **8** 19–31
Qin J, Duan W, Zou S, Chen Y, Huang W and Rosa L 2024 Global energy use and carbon emissions from irrigated agriculture *Nat. Commun.* **15** 3084
Rasmussen F N, Malmqvist T, Moncaster A, Wiberg A H and Birgisdóttir H 2018 Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings *Energy Build.* **158** 1487–98
Röck M, Saade M R M, Balouktsi M, Rasmussen F N, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T and Passer A 2020 Embodied GHG emissions of buildings—the hidden challenge for effective climate change mitigation *Appl. Energy* **258** 114107
Rosenzweig C *et al* na Modeling mitigation and adaptation co-benefits in rice systems in Bangladesh (CABI A&B) (Submitted)
Rosenzweig C, Tubiello F N, Sandalow D, Benoit P and Hayek M N 2021 Finding and fixing food system emissions: the double helix of science and policy *Environ. Res. Lett.* **16** 061002
Rust N A *et al* 2020 How to transition to reduced-meat diets that benefit people and the planet *Sci. Total Environ.* **718** 137208
Saifuddin M, Abramoff R Z, Foster E J and McClelland S C 2024 Soil carbon offset markets are not a just climate solution *Front. Ecol. Environ.* **22** e2781
Schneider K R *et al* 2023 The state of food systems worldwide in the countdown to 2030 *Nat. Food* **4** 1090–110
Shcherbak I, Millar N and Robertson G P 2014 Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen *Proc. Natl Acad. Sci. USA* **111** 9199–204
Shumba A, Chikowo R, Corbeels M, Six J, Thierfelder C and Cardinael R 2023 Long-term tillage, residue management and crop rotation impacts on N_2O and CH_4 emissions from two contrasting soils in sub-humid Zimbabwe *Agric. Ecosyst. Environ.* **341** 108207
Sims R, Flammini A, Puri M and Bracco S 2015 Opportunities for agri-food chains to become energy-smart FAO (available at: http://hdl.handle.net/10179/11462)
Smith P, Reay D and Smith J 2021 Agricultural methane emissions and the potential formitigation *Phil. Trans. R. Soc.* A **379** 20200451
Søndergaard N, Fernandes J F A, Potent J, Karl K, Furtado M and Baethgen W 2023 A governance framework to manage the food-environment-livelihood trilemma of alternative proteins *One Earth* **6** 843–53
Springmann M *et al* 2018 Options for keeping the food system within environmental limits *Nature* **562** 519–25
Stehfest E and Bouwman L 2006 N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions *Nutr. Cycling Agroecosyst.* **74** 207–28
Trishant D and Krishnamurthy R 2024 Unearthing reality: a DTE-CSE probe into the workings of the Indian voluntary carbon market (available at: www.downtoearth.org.in/news/climate-change/unearthing-reality-a-dte-cse-probe-into-the-workings-of-the-indian-voluntary-carbon-market-92094) (Accessed 28 March 2024)
Tubiello F N *et al* 2021a Greenhouse gas emissions from food systems: building the evidence base *Environ. Res. Lett.* **16** 65007
Tubiello F N 2021b *Methods for Estimating Greenhouse Gas Emissions from Food Systems: Part III: Energy Use in Fertilizer Manufacturing, Food Processing, Packaging, Retail and Household Consumption* (FAO) (https://doi.org/10.4060/cb7473en)
Tubiello F N *et al* 2022a Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems *Earth Syst. Sci. Data* **14** 1795–809
Tubiello F N, Crippa M, Karl K, Solazzo E, Cerilli S, Flammini A and Leip A 2022b Making food transport data matter *Nat. Food* **3** 12
Tubiello F N, Salvatore M, Rossi S, Ferrara A, Fitton N and Smith P 2013 The FAOSTAT database of greenhouse gas emissions from agriculture *Environ. Res. Lett.* **8** 015009
Vermeulen S J, Campbell B M and Ingram J S I 2012 Climate change and food systems *Annu. Rev. Environ. Resour.* **37** 195–222
von Braun J, Afsana K, Fresco L, Hassan M and Torero M 2021 Food systems-definition, concept and application for the UN food systems summit *Sci. Innov.* **27** 2–7 (available at: www.un.org/sites/un2.un.org/files/2021/01/food_systems_concept_paper_scientific_group_draft_dec_20_2020.pdf)
Wang Y, Fang M, Lou Z, He H, Guo Y, Pi X, Wang Y, Yin K and Fei X 2024 Methane emissions from landfills differentially underestimated worldwide *Nat. Sustain.* **7** 496–507
Zhu J, Luo Z, Sun T, Li W, Zhou W, Wang X, Fei X, Tong H, Yin K and Yin K 2023 Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems *Nat. Food* **4** 247–56