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Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems

Francesco N. Tubiello[1], Kevin Karl[1,2], Alessandro Flammini[1,3], Johannes Gütschow[4], Griffiths Obli-Laryea[1], Giulia Conchedda[1], Xueyao Pan[1], Sally Yue Qi[2], Hörn Halldórudóttir Heiðarsdóttir[1], Nathan Wanner[1], Roberta Quadrelli[5], Leonardo Rocha Souza[6], Philippe Benoit[2], Matthew Hayek[7], David Sandalow[2], Erik Mencos Contreras[8,9], Cynthia Rosenzweig[8,9], Jose Rosero Moncayo[1], Piero Conforti[1], and Maximo Torero[1]

[1]Food and Agriculture Organization, Rome, Italy
[2]Center on Global Energy Policy, Columbia University, New York, USA
[3]Department of Environment, United Nations Industrial Development Organization, Vienna, Austria
[4]Department of Transformation Pathways, Potsdam Institute for Climate Impact Research, Potsdam, Germany
[5]International Energy Agency, Paris, France
[6]United Nations Statistics Division, New York, USA
[7]Department of Environmental Studies, New York University, New York, USA
[8]Center for Climate Systems Research, Columbia University, New York, USA
[9]Climate Impacts Group, NASA Goddard Institute for Space Studies, New York, USA

Correspondence: Francesco N. Tubiello (francesco.tubiello@fao.org)

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Abstract. We present results from the FAOSTAT emissions shares database, covering emissions from agri-food systems and their shares to total anthropogenic emissions for 196 countries and 40 territories for the period 1990–2019. We find that in 2019, global agri-food system emissions were 16.5 (95 %; CI range: 11–22) billion metric tonnes (Gt CO_2 eq. yr^{-1}), corresponding to 31 % (range: 19 %–43 %) of total anthropogenic emissions. Of the agri-food system total, global emissions within the farm gate – from crop and livestock production processes including on-farm energy use – were 7.2 Gt CO_2 eq. yr^{-1}; emissions from land use change, due to deforestation and peatland degradation, were 3.5 Gt CO_2 eq. yr^{-1}; and emissions from pre- and post-production processes – manufacturing of fertilizers, food processing, packaging, transport, retail, household consumption and food waste disposal – were 5.8 Gt CO_2 eq. yr^{-1}. Over the study period 1990–2019, agri-food system emissions increased in total by 17 %, largely driven by a doubling of emissions from pre- and post-production processes. Conversely, the FAOSTAT data show that since 1990 land use emissions decreased by 25 %, while emissions within the farm gate increased 9 %. In 2019, in terms of individual greenhouse gases (GHGs), pre- and post-production processes emitted the most CO_2 (3.9 Gt CO_2 yr^{-1}), preceding land use change (3.3 Gt CO_2 yr^{-1}) and farm gate (1.2 Gt CO_2 yr^{-1}) emissions. Conversely, farm gate activities were by far the major emitter of methane (140 Mt CH_4 yr^{-1}) and of nitrous oxide (7.8 Mt N_2O yr^{-1}). Pre- and post-production processes were also significant emitters of methane (49 Mt CH_4 yr^{-1}), mostly generated from the decay of solid food waste in landfills and open dumps. One key trend over the 30-year period since 1990 highlighted by our analysis is the increasingly important role of food-related emissions generated outside of agricultural land, in pre- and post-production processes along the agri-food system, at global, regional and national scales. In fact, our data show that by 2019, pre- and post-production processes had overtaken farm gate processes to become the largest GHG component of agri-food system emissions in Annex I parties (2.2 Gt CO_2 eq. yr^{-1}). They also more than doubled in non-Annex I parties (to 3.5 Gt CO_2 eq. yr^{-1}), becoming larger than emissions from land use change. By 2019 food supply chains had become the largest agri-food system component in China (1100 Mt CO_2 eq. yr^{-1}), the USA (700 Mt CO_2 eq. yr^{-1}) and the EU-27 (600 Mt CO_2 eq. yr^{-1}). This has important repercussions for food-relevant national mitigation strategies, considering that until recently these have focused mainly on reductions of non-CO_2 gases within the farm gate and on CO_2 mitigation from land use change. The information used in this work is available as open data with DOI https://doi.org/10.5281/zenodo.5615082 (Tubiello et al., 2021d). It is also available to users via the FAOSTAT database (https://www.fao.org/faostat/en/#data/EM; FAO, 2021a), with annual updates.

1 Introduction

Agriculture is a significant contributor to climate change as well as one of the economic sectors most at risk from it. Greenhouse gas (GHG) emissions generated within the farm gate by crop and livestock production and related land use change contribute about one-fifth to one-quarter of total emissions from all human activities, when measured in CO_2 equivalents (Mbow et al., 2019; Smith et al., 2014; Vermeulen et al., 2012). The impacts are even starker in terms of individual GHG emissions. Agriculture contributes nearly 50 % of global anthropogenic methane (CH_4) and 75 % of the total nitrous oxide (N_2O) emissions (FAO, 2021b; Gütschow et al., 2021; Saunois et al., 2020). Once pre- and post-production activities along agri-food systems supply chains are included, food and agriculture activities generate up to one-third of all anthropogenic emissions globally (Crippa et al., 2021a, b; Rosenzweig et al., 2020; Tubiello et al., 2021a). This larger food system perspective expands the potential for designing GHG mitigation strategies across the entire food system, i.e., over and above the more traditional focus on agricultural production and land use management that is currently found within countries' nationally determined contributions (Crumpler et al., 2021).

Significant progress has recently resulted in the development of novel databases with global coverage of country-level data on agri-food system emissions (Crippa et al., 2021a, b; Tubiello et al., 2021a). Tubiello et al. (2021a), in particular, provided a mapping of emission categories of the Intergovernmental Panel on Climate Change (IPCC) – used by countries for reporting their national GHG inventories (NGHGI) to the United Nations Framework Convention on Climate Change (UNFCCC) – unto internationally accepted food and agriculture concepts that are more easily understood by farmers and planners in countries, including in ministries of agriculture. By providing a correspondence between IPCC and FAO terminology, we seek to help countries to more adequately capture important aspects of food and agriculture activities within existing climate reporting, so that they can better identify effective climate actions across their agri-food systems (Fig. 1, adapted from Tubiello et al., 2021a). Firstly, the correspondence mapping expands the IPCC "agriculture" definition to include, in addition to non-CO_2 emissions from the farm, also the CO_2 generated in drained peatlands on agricultural land (Conchedda and Tubiello, 2020; IPCC, 2014b) and by energy use in farm operations (FAO, 2011, 2014, 2020b; Flammini et al., 2022, Sims and Flammini, 2014). Secondly, it usefully disaggregates the land use, land use change and forestry (LULUCF) of IPCC (2003) by separating out the emissions directly linked to food and agriculture activities, such as those generated by deforestation (Curtis et al., 2018; Tubiello et al., 2021c) and peat fires (Prosperi et al., 2020), from carbon removals, which are largely associated with processes in managed forests rather than on agricultural land (Grassi et al., 2021).

We present herein and discuss results from the first agri-food system emissions database in FAOSTAT. The new database covers, as in previous versions (Tubiello et al., 2013), agriculture production activities within the farm gate and associated land use and land use change emissions on agricultural land. Importantly, it also includes estimates of emissions from pre- and post-production processes along food supply chains, including fertilizer manufacturing, energy use within the farm gate, food processing, domestic and international food transport, retail, packaging, household consumption, and food system waste disposal. The database provides emissions data for four main GHG gases/categories (CO_2, CH_4, N_2O and fluorinated gases) and their combined CO_2 equivalent (CO_2 eq.) levels. Data are available by country, over the period 1990–2019, as well as by regional and other relevant aggregations. Importantly, data are provided in both IPCC and FAO classifications, facilitating the identification of national mitigation strategies across agri-food systems in countries, regionally and globally.

2 Materials and methods

Recent work (Rosenzweig et al., 2021; Tubiello et al., 2021a) helped to characterize agri-food system emissions into three components: (1) farm gate, (2) land use change and (3) pre- and post-production. Emissions estimates from the first two – generated by crop and livestock production activities within the farm gate and by the conversion of natural ecosystems to agriculture, such as deforestation and peatland degradation – are well established (IPCC, 2019). In particular, FAO disseminates annual updates in FAOSTAT (FAO, 2021a, b; Tubiello, 2019). This paper expands the available FAOSTAT data to include estimates of emissions from pre- and post-production

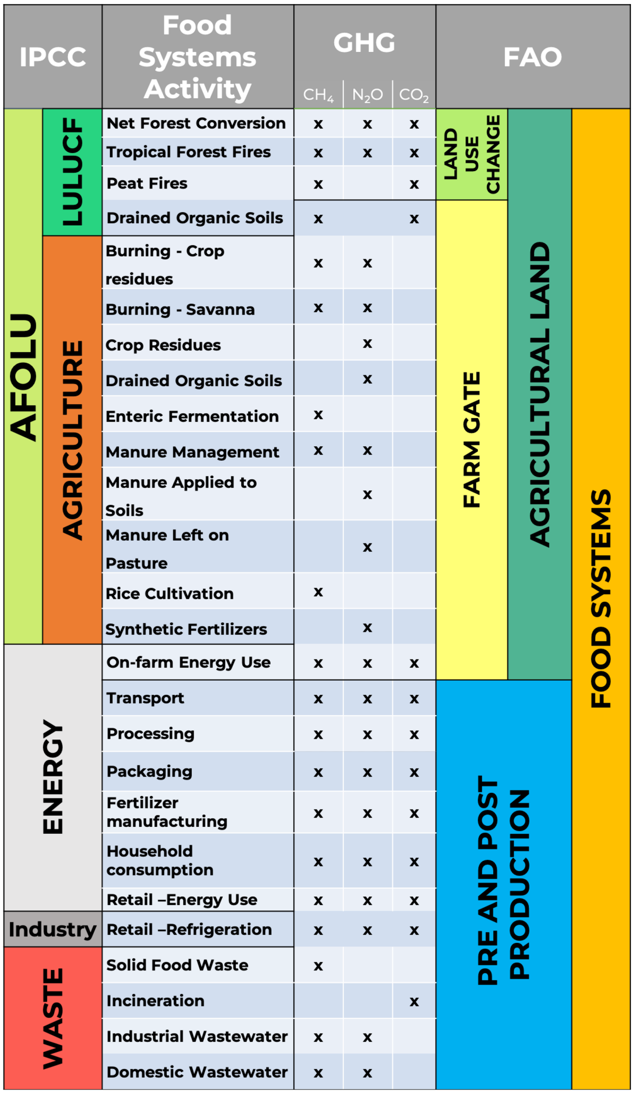

Figure 1. Mapping of emissions across agri-food systems. Left: IPCC sectors and processes used in national GHG emissions inventories. Right: food and agriculture sectors and categories aligned to FAO's definitions.

processes, including energy use in fertilizer manufacturing, food processing, packaging, transport, retail, household consumption, and waste disposal.

2.1 Mapping agri-food system components

The new FAOSTAT data are provided, for each country, in both IPCC and FAO classifications. Specifically, on the one hand, data can be downloaded using the following IPCC emissions categories: energy; industrial processes and product use (IPPU, henceforth referred to as industry); waste; agriculture; land use, land use change and forestry (LULUCF); and other. The total emissions from IPCC sectors are provided, as well as the portion directly related to agri-food systems. On the other hand, through the IPCC to FAO mapping discussed above and extending previous work (Tubiello et al., 2021a), data can also be downloaded in relevant FAO categories, covering emissions from farm gate, land use change, and pre- and post-production processes (Fig. 1).

The FAOSTAT emissions estimates follow the IPCC (2006) "territorial approach"; i.e., they are assigned to the countries where they occur, independently of production or consumption considerations. For example, CO_2 emissions from energy use in fertilizer manufacturing are accounted for in the producing country, while the N_2O emissions from fertilizer used on a country's agricultural land for crop production are accounted for in that country. Similarly, emissions from energy use in agri-food system activities are accounted for in countries where fuel combustion for that particular activity occurs, including electricity generation. The methods applied herein do not cover additional, upstream emissions associated with fuel supply chains, which are therefore not assigned to agri-food systems. More details on the scope of this work are found in Sect. 2.3.

2.2 Emissions estimates

FAO regularly disseminates emissions data for 15 subdomains in relation to the farm gate and land use change components of agri-food system emissions, with published methodologies and results (i.e., Tubiello et al., 2021a). This paper relies in addition on new methods for computing emissions from pre- and post-production processes. Specifically, methods for emissions from energy use in fertilizer manufacturing, food processing, retail, and household consumption as well as refrigeration in retail are presented in Tubiello et al. (2021b), while Karl and Tubiello (2021a, b) presented methods for estimating agri-food system emissions in transport and waste disposal. Finally, emissions from on-farm energy use were developed by Flammini et al. (2022). We refer the interested reader to those original publications for full details, while for completeness we also provide a sufficiently detailed summary of methods and coefficients as the Supplement of this paper.

More generally, a step-wise approach was followed for the estimation of agri-food system emissions, as follows.

- *Step 1*. Identify, for each food system component the relevant international statistics needed to characterize country-level activity data (AD).
- *Step 2*. Determine the food-related shares of the activity data (AD_{food}) and assign relevant GHG emission factors (EFs) to each activity.
- *Step 3*. Implement the generic IPCC method for estimating GHG emissions (E_{food}), using inputs of activity data and emission factors from the first two steps, as follows:

$$E_{food} = EF \times AD_{food}. \quad (1)$$

– *Step 4*. Impute missing agri-food systems GHG emissions data by component. This step was limited to pre- and post-production processes and applied where country-specific activity data were lacking. The imputation method used PRIMAP, a complete dataset of emissions estimates for all IPCC sectors, by country, covering the period 1990–2019 (Gütschow et al., 2021). The PRIMAP dataset is already available in FAOSTAT for the computation of emissions shares of agriculture to the total anthropogenic total (FAO, 2021c; Tubiello et al., 2021a). It compiles all available information on GHG emissions by country, including from official reporting. It was used internationally as the basis for an early, first-order estimate of agri-food system shares in total GHG emissions (IPCC, 2019). Additionally, it was recently used in a UNFCCC synthesis report (UNFCCC, 2021) to assess world GHG emissions from all sectors in preparation of a stock take exercise that will be undertaken in 2022–2023 to assess countries' performance against their mitigation commitments under the Paris Agreement. The imputations in equation (1) were performed by applying to the PRIMAP sectoral emissions country-specific food system emissions shares (Tubiello et al., 2021b, for more details).

2.3 Global warming potentials used

The estimated emissions data expressed in CH_4 and N_2O gases were converted to CO_2 equivalents by using the 100-year global warming potentials (GWPs) of the IPCC (2014) Fifth Assessment Report and specifically GWP-$CH_4 = 28$; GWP-$N_2O = 265$; GWP-F-gases $= 5195$. The value for fluorinated gases (F-gases) was obtained as an average of several distinct products (Tubiello et al., 2021b).

2.4 Data uncertainty and limitations

2.4.1 Boundaries

The processes covered herein do not span all processes attributable to agri-food systems. In particular, the scope of this work does not include, by design, upstream GHG emissions in the fuel chain, such as petroleum refining, as well as methane leaks during extraction processes and piping. These are expected to be not negligible if considered. While emissions from such sources can be estimated using a fixed fuel chain coefficient for certain fuel supply chains (see Crippa et al., 2021a), the authors do not consider such sources to be within scope of this work. GHG emissions attributable to electricity generation are included in the scope of this work, which itself excludes upstream GHG emissions in the fuel chain used to generate electricity (Flammini et al., 2022; Tubiello et al., 2021b).

Conversely, emissions of fluorinated gases (F-gases) from household refrigeration and from climate-controlled transportation were not included for lack of available country-level data for disaggregated cold chain elements. However, one estimate suggests that the majority (over 60 %) of global food-related F-gas emissions occur in the retail stage, which is accounted for here in this work (International Institute of Refrigeration, 2021). Emissions from pesticide manufacturing were also not included due to the paucity of information and methodologies for their estimation at the country level, in contrast to advanced work in fertilizer manufacturing (Brentrup et al., 2016, 2018; IFS, 2019). Bellarby et al. (2008) estimated global emissions from pesticides manufacturing to be roughly 72 (range: 3–140) Mt CO2eq yr^{-1}, roughly 1 %–2 % of the pre- and post-production total estimated in this work.

2.4.2 Uncertainty

Uncertainties in FAOSTAT farm gate and land use change emissions estimates have been characterized elsewhere and computed in line with IPCC (2000, 2006) guidelines as ranging 30 %–70 % across component processes. For the purpose of this analysis, we assigned uncertainties of 30 % and 50 % respectively to the farm gate and land use change components of the FAOSTAT agri-food system emissions, in line with previous work (i.e., Tubiello et al., 2013, 2021b). The uncertainties in the estimates of pre- and post-production activities described herein are by contrast less documented. On the one hand, uncertainties in underlying energy activity data and emissions factors are typically lower than for the other two components, ranging 5 %–20 % (Flammini et al., 2022). On the other hand, the relative novelty in estimating food system shares for a range of activity data across many processes makes our estimates more uncertain, with heavy reliance on literature results from a subset of countries and regions that are necessarily extended to the rest of the world (Karl and Tubiello, 2021a). For this reason, we assigned an overall uncertainty of 30 % to the pre- and post-production component. This is higher than the uncertainty of the underlying energy processes but more in line with values used in recent work (Crippa et al., 2021a). As shown below, considering a roughly equal, one-third contribution of the three components and their assigned uncertainties, an overall uncertainty of 40 % was estimated for the agri-food system emissions totals, applicable to countries and regional aggregates.

The above uncertainties are meant only as first rough estimates, useful to determine tentative 95 % confidence intervals for the overall agri-food system component of FAOSTAT emissions. Significantly more research is needed for further refinements in future studies, in particular on better characterizing sub-regional and regional activity data and emissions coefficients, given the diversity in agri-food system typology and their dependence on physical geography and national socio-economic drivers. These limitations nonetheless reflect the paucity of activity data available to describe agri-food system components and their trends, globally and regionally. While knowledge and data exist for regions and countries such as the EU, USA China and India, much remains to be done in terms of regional and country-specific coverage.

2.4.3 Areas for advancement

Work towards estimating agri-food system emissions at the country level can be advanced in several ways. The present approach could be expanded on by including other country- and region-specific studies that estimate trends in energy consumption across a range of similar activities as proxies – regardless of whether or not they are distinctly related to food. Furthermore, other data sources could help explain and estimate variations in agri-food systems between countries, such as GDP per capita, urbanization levels, proxies for infrastructure and industrial development, and geographic and climate considerations. The development of a methodology to estimate emissions from pesticides could be explored, as it would help complement the understanding of emissions associated with chemical use in agriculture, in addition to fertilizers. Emissions from machinery manufacturing and from upstream GHG emissions in the fuel chain could also be added to further refine the analysis. This work could be further expanded by focusing on specific food commodities – requiring an additional focus on international trade and on supply and demand patterns (Dalin and Rodríguez-Iturbe, 2016). Such analysis would ultimately enable consumers to understand the full carbon footprint of particular commodities across global supply chains, which can facilitate GHG mitigation actions taken at the consumer level (Poore and Nemecek, 2018). Furthermore, it would be also useful to further investigate the increasing role of bioenergy and renewables as important mitigation opportunities in the food sector (Clark et al., 2020, Monforti et al., 2015; Pablo-Romero et al., 2017; Wang, 2014).

3 Results

3.1 Global trends

The FAOSTAT dataset considered in this study estimates in 2019 total anthropogenic emissions at 52 Gt CO_2 eq. yr^{-1} without land use, land use change and forestry emissions (LULUCF), as well as 54 Gt CO_2 eq. yr^{-1} with LULUCF – consistently with recent estimates (IPCC, 2019). We use the latter figure to compute emissions shares. In 2019 world total agri-food system emissions, expressed in terms of 95 % confidence intervals (CI) determined using an overall uncertainty of 40 %, were 16.5 (CI range: 10–23) billion metric tonnes (Gt CO_2 eq. yr^{-1}), corresponding to 31 % (range: 19 %–42 %) of total anthropogenic emissions (Table 1). Of the food system total, global emissions within the farm gate – from crop and livestock production processes including on-farm energy use – were 7.2 (range: 5–9) Gt CO_2 eq. yr^{-1}; emissions from land use change, due to deforestation and peatland degradation, were 3.5 (range: 2–5) Gt CO_2 eq. yr^{-1}; and emissions from pre- and post-production processes – manufacturing of fertilizers, food processing, packaging, transport, retail, household consumption and food waste disposal – were 5.8 (range: 4–8) Gt CO_2 eq. yr^{-1}. Over the study period 1990–2019, agri-food system emissions increased in total by 17 %, though they have remained rather constant since about 2006 (Fig. 2). These trends were largely driven by a doubling of emissions from pre- and post-production processes, while land use emissions decreased by 25 % and farm gate increased only 9 %. In terms of single GHG, pre- and post-production processes emitted the most CO_2 (3.9 Gt CO_2 yr^{-1}) in 2019, preceding land use change (3.3 Gt CO_2 yr^{-1}) and farm gate (1.2 Gt CO_2 yr^{-1}) emissions. Conversely, farm gate activities were by far the major emitter of methane (140 Mt CH_4 yr^{-1}) and of nitrous oxide (7.8 Mt N_2O yr^{-1}). Pre- and post-processes were also significant emitters of methane (49 Mt CH_4 yr^{-1}), mostly generated from the decay of solid food waste in landfills and open dumps.

Emissions from within the farm gate and those due to related land use processes, including details of their subcomponents, have been discussed in Tubiello et al. (2021a) and are regularly presented within FAOSTAT statistical briefs (e.g., FAO, 2020a, 2021b). Here we provide a detailed discussion of the components of agri-food system emissions from pre- and post-production activities along supply chains and their relative contribution to the food system totals (Fig. 3). Considering that the uncertainties used above are rough estimates, we will not report uncertainties in the following analysis. Our data show that in 2019 emissions from deforestation were the single largest emission component of agri-food systems, at 3.1 Gt CO_2 yr^{-1}, having decreased 30 % since 1990. The second most important components were non-CO_2 emissions from enteric fermentation (2.8 Gt CO_2 eq. yr^{-1}), with increases of 13 %. These were followed by emissions from livestock manure (1.3 Gt CO_2 eq. yr^{-1}) and several pre- and post-production emissions, including CO_2 from household consumption (1.3 Gt CO_2 eq. yr^{-1}), CH_4 from food waste disposal (1.3 Gt CO_2 eq. yr^{-1}), mostly CO_2 from fossil-fuel combustion for on-farm energy use (1.0 Gt CO_2 eq. yr^{-1}), and CO_2 and F-gases emissions from food retail (0.9 Gt CO_2 eq. yr^{-1}). Importantly, our data show that growth in pre- and post-production components was particularly strong, with emissions from retail increasing from 1990 to 2019 by more than 7-fold, while emissions from household consumption more than doubled over the same period.

Finally, while emissions from agri-food systems increased globally by 16 % between 1990 and 2019, their share in total emissions decreased, from 40 % to 31 %, as did the per capita emissions, from 2.7 to 2.1 t CO_2 eq. per capita (Fig. 2).

Table 1. GHG emissions (Mt CO_2 eq.) by agri-food system component for all processes considered in this work. Data on forestland removals are provided for completeness of land-based emissions available in FAOSTAT. Uncertainties (not shown) are estimated at 30 % for farm gate and pre- and post-production components and at 50 % for land use change processes.

Activity	Category	1990	2019	Change
Net forest conversion	Land use change	4392	3058	−30 %
Enteric fermentation	Farm gate	2494	2823	13 %
Livestock manure	Farm gate	1101	1315	19 %
Household consumption	Pre- and post-production	541	1309	142 %
Waste disposal	Pre- and post-production	984	1278	30 %
On-farm energy use	Farm gate	757	1021	35 %
Food retail	Pre- and post-production	128	932	631 %
Drained organic soils	Pre- and post-production	736	833	13 %
Rice cultivation	Farm gate	621	674	9 %
Fires	Land use change	558	654	17 %
Synthetic fertilizers	Farm gate	422	601	42 %
Food transport	Pre- and post-production	327	586	79 %
Food processing	Pre- and post-production	421	510	21 %
Fertilizer manufacturing	Pre- and post-production	152	408	168 %
Food packaging	Pre- and post-production	166	310	87 %
Crop residues	Farm gate	161	226	40 %
Forestland		−3391	−2571	−24 %

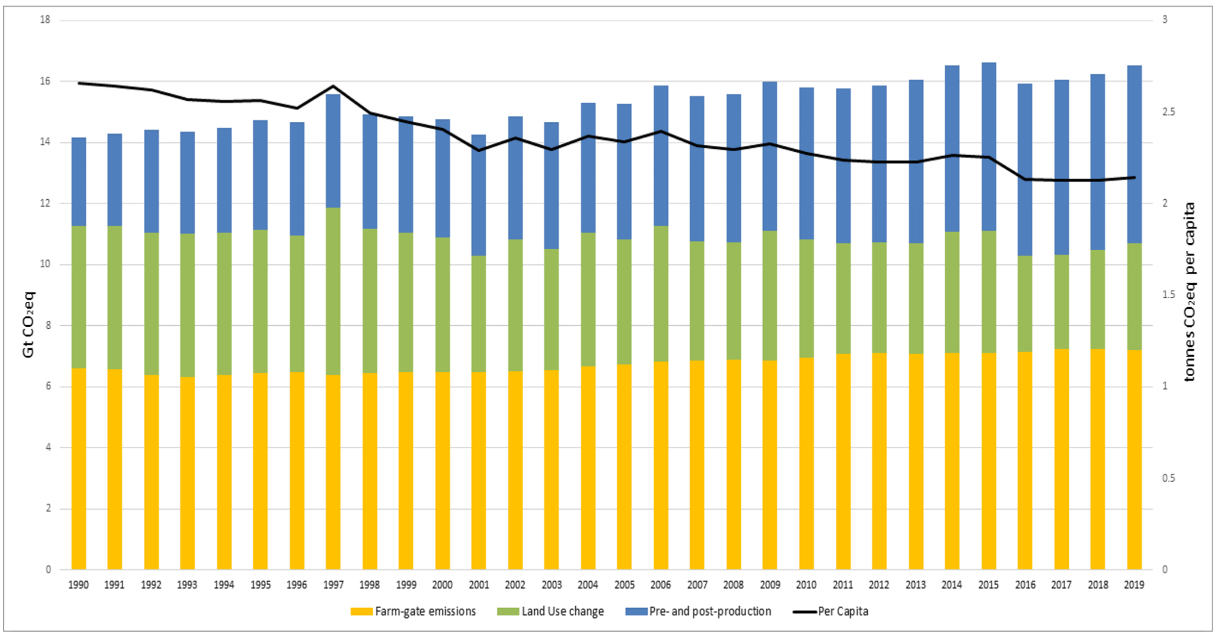

Figure 2. World total GHG emissions from agri-food systems, 1990–2019. Color bars show contributions by emissions within the farm gate (yellow); land use change (green) and pre- and post-production along food supply chains (blue). Source: FAOSTAT (FAO, 2021a). Also shown are emissions per capita (authors' own calculations).

3.2 Regional trends

Our results indicate significant regional variation in terms of the composition of agri-food system emissions by component (Fig. 4). Specifically, in terms of total agri-food system emissions in 2019, Asia had the largest contribution, at 7 Gt CO_2 eq. yr^{-1}, followed by Africa (2.7 Gt CO_2 eq. yr^{-1}), South America (2.4 Gt CO_2 eq. yr^{-1}) and Europe (2.1 Gt CO_2eq yr^{-1}). North America (1.5 Gt CO_2eq yr^{-1}) and Oceania (0.3 Gt CO_2eq yr^{-1}) were the smallest emitters among regions (Fig. 4). Focusing on GHG emissions beyond agricultural land, pre- and post-production emissions in 2019 were largest in Asia (2.9 Gt CO_2 eq. yr^{-1}), followed by Europe and North America (0.8–1.1 Gt CO_2 eq. yr^{-1}).

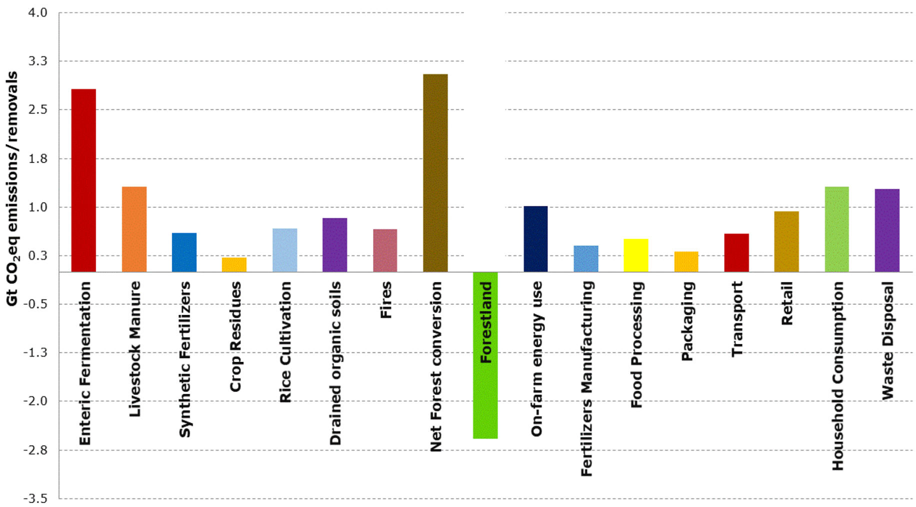

Figure 3. World total 2019 GHG emission from agri-food systems, showing contributions on agricultural land (left panel) and from pre- and post-production along food supply chains (right panel). Net removals on forest land are also shown, for completeness. The sum of emissions from agricultural land and forest land correspond to the IPCC AFOLU category. Source: FAOSTAT (FAO, 2021a).

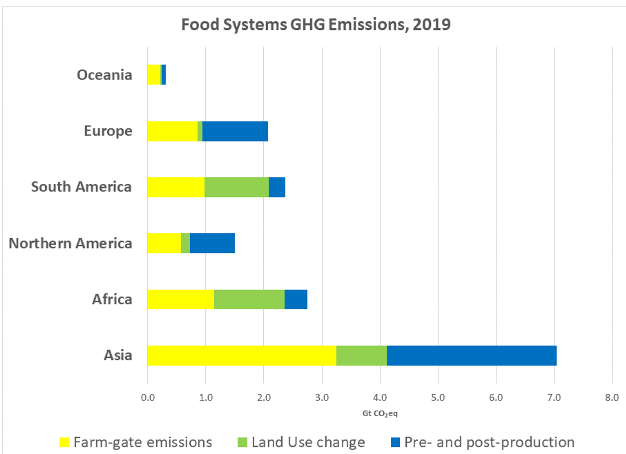

Figure 4. Total GHG emission from agri-food systems by FAO regions, 2019. Color bars show contributions by emissions within the farm gate (yellow), land use change (green), and pre- and post-production along food supply chains (blue). Source: FAOSTAT (FAO, 2021a).

Regions also varied in terms of how agri-food system components contributed to the total (Table 2). In 2019, pre- and post-production emissions were the largest food system contributor in Europe (55 %), North America (52 %) and Asia (42 %). Conversely, they were smallest in Oceania (23 %), Africa (14 %) and South America (12 %). Additionally, the contribution of pre- and post-production processes along food supply chains significantly increased since 1990, when in no region were they the dominant emissions component. Since then, they doubled in all regions except in Africa – where it remained below 15 %.

The data show which pre- and post-production process was most important by region (Table 2). In 2019, food household consumption was the dominant process outside of agricultural land emissions in Asia (0.9 Gt CO_2 eq. yr^{-1}) and Africa (0.2 Gt CO_2 eq. yr^{-1}). Conversely, Europe, Oceania and North America pre- and post-production processes were led by emissions from food retail (0.3–0.4 Gt CO_2 eq. yr^{-1}), while South America was dominated by emissions from food waste disposal (0.2 Gt CO_2 eq. yr^{-1}).

3.3 Country trends

Our estimates show a marked variation among countries in terms of total emissions as well as the composition of contributions across farm gate, land use change, and pre- and post-processing components (Fig. 5). China had the most emissions (1.9 Gt CO_2 eq. yr^{-1}), followed by India, Brazil, Indonesia and the USA (1.2–1.3 Gt CO_2 eq. yr^{-1}). The Democratic Republic of the Congo (DRC) and the Russian Federation followed with 0.5–0.6 Gt CO_2 eq. yr^{-1}, followed by Pakistan, Canada and Mexico with 0.2–0.3 Gt CO_2eq yr^{-1}. The contribution of the three main agri-food system components to the national total differed among countries significantly (Fig. 5). For instance, China and India had virtually no contribution from land use change to agri-food system emissions. The land use contribution was also minor in the USA, the Russian Federation and Pakistan. Conversely, the latter was the dominant emissions component in Brazil, Indonesia and the DRC. Additionally, the new database allowed for an in-depth analysis by country of pre- and post-production emissions along the agri-food chain, highlighting a significant variety in most relevant sub-process contribution (Table 3). For the year 2019, pre- and post-production emissions were dominated in China by food household

Table 2. Regional GHG emissions (Gt CO_2 eq.) by agri-food system component, showing farm gate, land use change (LUC), pre- and post-production processes (PPPs), and total emissions percentage contribution of PPPs shown for the year 1990 and 2019. The last two columns show the largest estimated contributing PPP activity by region. Uncertainties are estimated to be 30 % for farm gate and PPP activities and 50 % for land use change.

Region	Farm gate	LUC	PPP	Total	% PPP	% PPP (1990)	Highest PPP	note
Asia	3.2	0.9	2.9	7.0	42 %	24 %	0.9	Household
Africa	1.1	1.2	0.4	2.7	14 %	16 %	0.2	Household
South America	1.0	1.1	0.3	2.4	12 %	6 %	0.1	Waste
Europe	0.9	0.1	1.1	2.1	55 %	26 %	0.4	Retail
Northern America	0.6	0.2	0.8	1.5	52 %	35 %	0.3	Retail
Oceania	0.2	0.0	0.1	0.3	23 %	11 %	0.0	Retail

consumption processes (463 Mt CO_2 eq. yr^{-1}), whereas food waste disposal was the dominant pathway in Brazil, Indonesia (77 Mt CO_2 eq. yr^{-1}), DRC (8 Mt CO_2 eq. yr^{-1}), Pakistan (33 Mt CO_2 eq. yr^{-1}) and Mexico, (56 Mt CO_2eq yr^{-1}). Emissions from food retail dominated the pre- and post-production component in the USA (292 Mt CO_2 eq. yr^{-1}), the Russian Federation (177 Mt CO_2 eq. yr^{-1}) and Canada (20 Mt CO_2 eq. yr^{-1}). Finally, on-farm energy use was the largest pre- and post-production component in India (205 Mt CO_2 eq. yr^{-1}).

4 Discussion

4.1 Comparisons with previous work

The overall assessment of total agri-food system emissions found in this work confirms recent previous findings by the IPCC (2019) and Crippa et al. (2021a, b). With regards to pre- and post-production, the FAOSTAT estimates were consistent (Table 4) with previous findings (i.e., Crippa et al., 2021a, b; Vermuelen et al., 2012; Poore and Nemecek, 2018). In particular, emissions estimates for food transport, processing, waste and retail were consistent with EDGAR-FOOD (Karl and Tubiello, 2021b), and estimates for fertilizer manufacturing were in line with previous work by Vermeulen et al. (2012). Conversely, FAOSTAT estimates were higher than EDGAR-FOOD for household consumption and lower for food packaging, with the latter possibly linked to FAOSTAT estimates excluding indirect emissions from fuel supply chains, which were instead included in previously published estimates. Finally, our estimates of F-gas emissions from retail agreed well with those published in EDGAR-FOOD.

The most important disagreement with previous work was observed in relation to household consumption emissions. FAOSTAT estimates in this work, 1.2 Gt CO_2 eq., were nearly 3 times those of EDGAR-FOOD (with reference to 2015, the last year for which EDGAR data were available). While much more research is needed to refine estimates in this important agri-food system component, our estimates were in fact well aligned with earlier FAO (2011) work (Fig. 4), as well as more consistent with observed population growth, an important determinant of household consumption trends (Tao et al., 2018).

4.2 Trends

One notable trend over the 30-year period since 1990 is the increasingly important role of food-related emissions generated outside of agricultural land, in pre- and post-production processes along food supply chains, at all global, regional and national scales. Our data show that by 2019, pre- and post-production processes had overtaken farm gate processes to become the largest GHG component of agri-food system emissions in Annex I parties (2.2 Gt CO_2 eq. yr^{-1}). While farm gate emissions still dominated food system processes in non-Annex I parties, emissions from pre- and post-production were closing the gap in 2019, surpassing land use change and having doubled since 1990 to 3.5 Gt CO_2 eq. yr^{-1}. By 2019, pre- and post-production processes had become the largest agri-food system component in China (1.1 Gt CO_2 eq. yr^{-1}), the USA (0.7 Gt CO_2 eq. yr^{-1}) and the EU-27 (0.6 Gt CO_2 eq. yr^{-1}). This has important repercussions for food-relevant national mitigation strategies, such as those included in countries' nationally determined contributions, considering that until recently these have focused mainly on reductions of non-CO_2 gases within the farm gate and on CO_2 mitigation from land use change (Hönle et al., 2019).

Importantly, the FAOSTAT database presented here allows for an estimation of the percentage share contribution of food system emissions in total anthropogenic emissions, by country as well as at regional and global levels, over the period 1990–2019. A number of important issues can be highlighted to this end (Table 5 and Fig. 6). First, in terms of CO_2 eq., the share of world total agri-food system emissions decreased from 40 % in 1990 to 31 % in 2019. Thus, while it is important to note that one-third of all GHG emissions today are generated by agri-food systems, their shares in total emissions may continue to decrease in the near future. This decreasing trend was driven by trends in large regions, consistently with transformations in their agri-food systems and

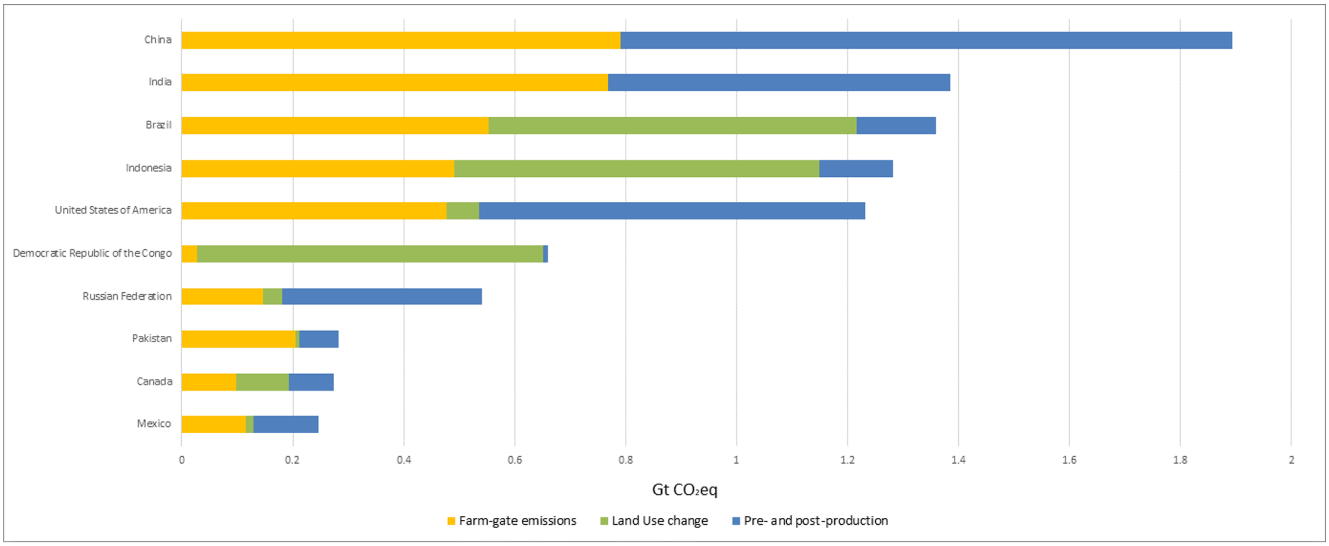

Figure 5. Total GHG emission from agri-food systems by country, top 10 emitters, 2019. Color bars show contributions by emissions within the farm gate (yellow), land use change (green), and pre- and post-production along food supply chains (blue). Source: FAOSTAT (FAO, 2021a).

Table 3. Top 10 country GHG emissions (Mt CO_2 eq.) by agri-food system component and total food system emissions, 2019. The last two columns show the dominant sub-component of pre- and post-production processes. Agri-food system GHG emissions from the top 10 countries represent 55 % of global agri-food system emissions. Country-level uncertainties are those used for global and regional estimates.

Country	Farm gate	LUC	PPP	Total	Main PPP	Main PPP name
China	792	0	1102	1894	469	Household consumption
India	768	0	618	1386	205	On-farm
Brazil	553	663	144	1360	79	Waste disposal
Indonesia	491	658	132	1281	76	Waste disposal
USA	477	60	696	1232	292	Retail
DRC	28	624	9	660	8	Waste disposal
Russian Federation	146	35	362	542	177	Retail
Pakistan	205	7	71	283	33	Waste disposal
Canada	97	96	81	274	20	Retail
Mexico	115	15	116	246	56	Waste disposal

land use change patterns. For instance, in South America, the region with the highest food system share over the entire study period (Fig. 6), food shares decreased from 96 % in 1990 to 72 % in 2019, in Africa from 67 % to 57 %, in Asia from 49 % to 24 %, and in Oceania from 57 % to 39 %. In contrast to these trends, our data suggested that in regions dominated by modern agri-food systems, such as Europe and North America, the overall share of agri-food system emissions in fact increased from 1990 to 2019, specifically from 24 % to 31 % in Europe and from 17 % to 21 % in North America. Such increases could be explained by increases in absolute emissions from pre- and post-production activities (Table 5), re-enforced by concomitant emissions decreases in the non-food sector, especially energy systems (Lamb et al., 2022). The noted increase in absolute emissions from pre- and post-production activities was in fact present in all regions, leading to increases in the relative contributions to agri-food systems of this component, except for Africa.

An analysis on agri-food system impacts on total GHG emissions would not be complete without a focus on component gases in addition to quantities expressed in CO_2 eq.. The FAOSTAT data confirm the trends form 1990 to 2019 seen for total CO_2 eq. emissions, with important features (Table 6). First, the impact of agri-food systems on world total CO_2 emissions was 21 % in 2019 (down from 31 % in 1990), a respectable share considering the importance of carbon dioxide in any effective long-term mitigation strategy. While most regions had contributions around this value, ranging 13 %–23 % for North America, Oceania, Europe and Asia, the CO_2 contribution of agri-food systems was highest in Africa (52 %) and South America (70 %), largely in relation to land use change emissions, still significant therein. Europe and

Table 4. Overview of pre- and post-food production GHG emission estimates from selected studies, Gt CO_2eq. Adapted from Tubiello et al. (2021b).

Food system component	FAO (2011)[1]	Vermeulen et al. (2012)[2]	Poore and Nemecek (2018)[3]	Ritchie (2019)[4]	Tubiello et al. (2021a)[5]	Crippa et al. (2021a, b) EDGAR-FOOD[6]	This analysis[6]
Reference year	Mid-2000s	2004–2007	2009–2011	2017	2019	2015	2019
Fertilizer manufacturing	–	0.3–0.6	–	–	–	–	0.4
Food processing	2.1	0.2	0.6	0.5	4.3 (including retail and household consumption)	0.5	0.5
Food packaging		0.4	0.6	0.7		1.0	0.3
Food transport			0.8	0.8	0.5	0.9	0.6
Food retail		0.7	0.4	0.4		0.8	0.9
Food household consumption	1.2	0.2	–	–		0.5	1.3
Waste disposal	–	0.1	–	–	1.0	1.6	1.3
On-farm electricity generation	–	–	–	–	–	–	0.5
TOTAL	3.3	1.9–2.2	2.4	2. 4	5.8	5.3	5.8

[1] Includes emissions from indirect energy inputs (e.g., manufacturing of machinery). Global estimate based on literature. [2] Global estimate based on Chinese and British emission patterns and literature. [3] Meta-analysis of life-cycle assessments. [4] Global estimate based on literature. [5] Global estimate largely based on country-level (bottom-up) analysis (relying on FAOSTAT and EDGAR-FOOD). [6] Global estimate largely based on country-level (bottom-up) analysis.

Table 5. Regional GHG emissions (Mt CO_2 eq.) by agri-food system component and total food system emissions, 2019. The last two columns show the dominant sub-component of pre- and post-production processes. Uncertainties (not shown) are estimated at 30 % for farm gate and pre- and post-production components and at 50 % for land use change processes.

	Farm gate		Land use change		Pre- and post-production		Agri-food system total	
	1990	2019	1990	2019	1990	2019	1990	2019
Africa	705 23 %	1139 24 %	1017 33 %	1220 26 %	323 11 %	388 8 %	2045 67 %	2747 57 %
Asia	2595 25 %	3250 11 %	1273 12 %	865 3 %	1223 12 %	2930 10 %	5091 49 %	7044 24 %
Europe	1603 16 %	854 13 %	88 1 %	83 1 %	589 6 %	1140 17 %	2280 23 %	2077 31 %
North America	538 8 %	574 8 %	175 3 %	156 2 %	376 6 %	777 11 %	1089 17 %	1507 21 %
South America	728 23 %	982 30 %	1974 64 %	1106 34 %	176 6 %	281 9 %	2878 93 %	2369 72 %
Oceania	267 40 %	223 28 %	65 10 %	16 2 %	42 6 %	71 9 %	374 57 %	309 39 %
World	6604 19 %	7214 13 %	4676 13 %	3503 6 %	2886 8 %	5827 11 %	14 165 40 %	16 544 31 %

North America were the only regions where the CO_2 share of agri-food systems actually increased from 1990 to 2019, confirming the growing weight of pre- and post-production processes, which typically involve fossil-fuel energy use and thus emissions of CO_2 gas through combustion. Second, the data highlight the significant contribution of agri-food systems to 2019 world total emissions of CH_4 (53 %) and N_2O (78 %), also confirmed at regional levels (Table 6), linked to farm gate production processes (Tubiello, 2019).

Finally, the data highlight a very large increase in agri-food system contributions of F-gas emissions, which went from near zero in 1990 to more than one-quarter of the world total in 2019 – with larger contributions in many regions. Such a marked increase is consistent with the growth in use of hydrofluorocarbons (HFCs) as refrigerants in the food retail and other sectors, following the banning of chlorofluorocarbons (CFCs) in 1990 (Fang et al., 2018; Hart et al., 2020; International Institute of Refrigeration, 2021; Tubiello

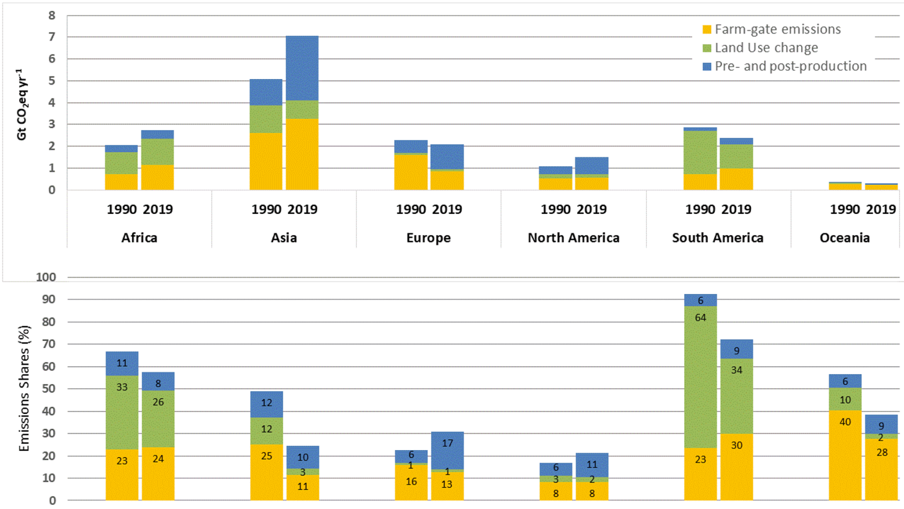

Figure 6. Top panel: agri-food system emissions (Gt CO_2 eq. yr^{-1}). Bottom panel: shares of agri-food systems in total anthropogenic emissions (%). Data shown by region, 1990–2019. Color bars show contribution components: farm gate (yellow), land use change (green), and pre- and post-production along food supply chains (blue). Source: FAOSTAT (FAO, 2021a).

Table 6. World total and regional GHG agri-food system emissions shares (%), 1990–2019, by single gas and CO_2 eq.. Uncertainties in shares (not shown) are the same as those estimated for absolute emissions. See Crippa et al. (2021a) for a specific list of hydrofluorocarbons (HFCs) used in agri-food systems, which form the basis of the F-gas emissions data estimated in this work.

	1990	2019	1990	2019	1990	2019	1990	2019	1990	2019
	CO_2 eq.		CO_2		CH_4		N_2O		F-gases	
World	40	31	31	21	60	53	79	78	0	27
Africa	67	57	65	52	63	58	90	87	0	20
Northern America	17	21	11	13	36	42	60	70	0	56
South America	93	72	97	70	82	75	94	92	0	6
Asia	49	24	38	16	66	49	84	80	0	9
Europe	23	31	13	23	46	47	70	74	0	28
Oceania	57	39	38	22	76	64	93	77	0	63

et al., 2021b)). Our findings are furthermore consistent with the strong growth in F-gas emissions reported in recent studies (Minx et al., 2021; Park et al., 2021).

An important aspect of the dataset presented in this study is its provision of information mapped across IPCC and FAO categories alike. Specific IPCC sectors include agriculture and land use, land use change and forestry (LULUCF). The IPCC further considers the agriculture, forestry and other land use (AFOLU). While countries report their agriculture and food emissions to the UNFCCC within national GHG inventories, our findings highlight the importance of expanding that reporting to a fuller agri-food systems view, one that properly weights the contribution of food to the global economy. Indeed, our results show that agri-food system emissions in 2019 were one-third of total anthropogenic emissions. This important picture does not emerge from NGHGI reporting aligned to IPCC categories, according to which, for instance, LULUCF and AFOLU emissions contributed respectively 4 % and 15 % of the total.

5 Data availability

The GHG emission data presented herein cover the period 1990–2019 at the country level, with regional and global aggregates. They are available as open data, with DOI https://doi.org/10.5281/zenodo.5615082 (Tubiello et al., 2021d), and via the FAOSTAT emissions shares database (https://www.fao.org/faostat/en/#data/EM, FAO, 2021a).

6 Conclusions

This paper provided details of a new FAOSTAT database on GHG emissions along the entire agri-food systems chain, including crop and livestock production processes on the farm, land use change activities from the conversion of natural ecosystems to agricultural land, and processes along food supply chains, from input manufacturing to food processing, transport and retail, including household consumption and waste disposal.

The data are provided in open-access mode to users worldwide and are available by country over the time period 1990–2019, with plans for annual updates. The major trends identified in this work help locate GHG emissions hotspots in agri-food systems at the country, regional and global level. This can inform the process of designing effective mitigation actions in food and agriculture. This work adds to knowledge on GHG emissions from agriculture and land use – generally well established in the literature – by adding critical information on emissions from a range of pre- and post-production processes. The new data highlight the increasingly important role that pre- and post-production processes along supply chains play in the overall GHG footprint of agri-food systems, globally and in most countries, providing new insights into food and agriculture development trends and future mitigation options.

The granularity of the dataset allows us, for the first time, to highlight specific processes of importance in specific countries or groups of countries with similar characteristics. The relevance of the information being provided cuts across several national and international priorities, specifically those aiming at achieving more productive and sustainable food systems, including in relation to climate change. To this end, the work presented herein completes a mapping of IPCC categories, used by countries for reporting to the climate convention, to food and agriculture categories that are more readily understandable by farmers and ministries of agriculture in countries. This helps better identify agri-food system entry points within existing and future national determined contributions. Finally, the methodological work underlying these efforts complements and extends recent pioneering efforts by FAO and other groups in characterizing technical coefficients to enable quantifying the weight of agri-food systems within countries' emissions profiles. The next steps in such efforts would need the involvement of interested national and international experts in compiling a first set of coefficients for agri-food systems as a practical agri-food systems annex to the existing guidelines of the Intergovernmental Panel on Climate Change, providing guidance to countries on how to better characterize food and agriculture emissions within their national GHG inventories.

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