Pre- and post-production processes ~~along supply chains~~ increasingly dominate greenhouse gas~~GHG~~ emissions from agri-food systems ~~globally and in most countries~~

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-Contrera[8,9], Cynthia Rosenzweig[9,8], 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]United Nations Industrial Development Organization, Department of Environment, Vienna, Austria
[4]Potsdam Institute for Global Climate Research, Potsdam, Germany
[5]International Energy Agency, Paris, France
[6]United Nations Statistics Division, New York, USA
[7]Department of Environmental Science, New York University, New York, USA
[8]Center of Global Climate Research, Columbia University, New York, USA
[9]NASA Goddard Institute for Space Studies, New York, USA

Corresponding author: Francesco N. Tubiello, francesco.tubiello@fao.org

Abstract. We present results from the FAOSTAT ~~*agri-food systems* ~~*Emissions shares* database, ~~relative to~~covering emissions from agri-food systems and their shares to total anthropogenic emissions for 196 ~~236~~ countries and 40 territories, ~~and~~ for ~~over~~ the period 1990-2019. We find that in 2019, ~~world-total~~global agri-food systems emissions were 16.5~~6.5~~ (95% CI range: 11-22) billion metric tonnes (Gt CO_{2eq} yr^{-1}), corresponding to 31% (range: 19-43%) of total anthropogenic emissions. Of the agri-food systems total, global emissions within the farm gate—from crop and livestock production processes including on-farm energy use—were 7.2 Gt CO_{2eq} yr^{-1}; emissions from land use change, due to deforestation and peatland degradation, were 3.5 Gt CO_{2eq} 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_{2eq} yr^{-1}. Over the study period 1990-2019, agri-food systems 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 ~~only~~ 9%. In 2019, in terms of ~~single GHG~~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. ~~The most important~~One key trend over the 30-

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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 ~~food supply chains~~the agri-food system, at ~~at all scales from~~ global, regional and national scales~~, from 1990 to 2019~~. In fact, our data show that by 2019, ~~food supply chains~~pre- and post-production processes had overtaken farm-gate processes to become the largest GHG component of agri-food systems emissions in Annex I parties (2.2 Gt CO_{2eq} yr^{-1}). They also more than doubled in non-Annex I parties (to 3.5 Gt CO_{2eq} 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_{2eq} yr^{-1}); USA (700 Mt CO_{2eq} yr^{-1}) and EU-27 (600 Mt CO_{2eq} 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 ~~(Hönle et al., 2019)~~. The information used in this work is available as open data with DOI 10.5281/zenodo.5615082 ~~at: https://zenodo.org/record/5615082~~ (Tubiello et al., 2021d). It is also available to users via the FAOSTAT database (FAO, 2021a), with annual updates.

Keywords: Agri-food systems, GHG emissions, farm gate, land use change, supply chains

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1. Introduction

Agriculture is a significant contributor to climate change as well as one of the ~~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). ~~In terms of single gases, impacts are even starker~~The impacts are even starker in terms of individual GHG emissions. Agriculture contribute nearly 50% of ~~world total~~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 systems perspective expands the potential for designing GHG mitigation strategies ~~that can address options in food and agriculture~~ 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 (FAO, 2019).

Significant progress has recently resulted in the development of novel databases with global coverage of country-level data on agri-food systems 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 ~~climate~~ reporting ~~by countries of~~their national GHG inventories (NGHGI) to the United Nations Framework Convention on Climate Change (UNFCCC)~~—,~~ ~~to more relevant~~unto internationally accepted food and agriculture concepts that~~, developed by FAO and used to disseminate food and agriculture statistics in FAOSTAT,~~ are more easily understood by farmers and planners in countries, including in Ministries of Agriculture. ~~Such mapping allows to more~~~~could~~By providing a correspondence between IPCC and FAO terminology, we seek to help~~enable~~ countries to more adequately capture important aspects of food and agriculture activities within existing climate reporting~~ (Fig. 1, adapted from Tubiello et al., 2021a)~~, so that they can better identify effective climate actions across their agri-food systems (Fig. 1, adapted from Tubiello et al., 2021a). Firstly, ~~it~~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; Drösler et al., 2014) and by~~through~~ energy use in farm operations (FAO, 2020b; Flammini et al., 2021; Sims and Flammini, 2014). Secondly, it usefully disaggregates the 'Land Use, land use change and forestry' (LULUCF) of IPCC (2003) ~~used in NGHGI,~~ by separating out ~~carbon sinks from land-based~~the emissions ~~sources that are more~~ directly linked to food and agriculture activities, such as those generated by deforestation (Curtis et al., 2020; Tubiello et al., 2021c) and peat fires (Prosperi et al., 2020), from carbon removals, which are largely associated to processes in managed forests rather than on agricultural land (Grassi et al., 2021).

We present herein and discuss results from the first agri-food systems emissions database in FAOSTAT~~ of food and agriculture emissions~~. 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 systems waste disposal. The ~~new~~

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~~FAOSTAT~~ database provides ~~information of~~ emissions data ~~of the~~for four main GHG gases/categories~~es~~ (CO_2, CH_4, N_2O and ~~F-gas~~fluorinated gases)~~s,~~ ~~as well as~~and their combined CO_2eq 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~~We examine new results and discuss how they can inform~~ national mitigation strategies across agri-food systems ~~that are relevant to food and agriculture in~~ in countries, regionally and globally.

2. Materials and methods

Recent work (Rosenzweig et al., 2021; Tubiello et al., 2021a) helped to characterize agri-food systems 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—~~have been long~~are well established (IPCC, 2019). In particular, FAO ~~and data are regularly~~ disseminates annual updates~~d~~ in FAOSTAT (FAO, 2021; Tubiello, 2019). This paper expands the available FAOSTAT data to include estimates of emissions from~~adds~~ pre- and post-production processes, ~~emissions~~, ~~along food supply and waste chains outside of agricultural land~~, including ~~those generated from~~ energy use in fertilizer manufacturing; food processing; packaging; transport; retail; household consumption; and waste disposal.

2.1 Mapping Agri-food Systems Components

The new FAOSTAT ~~Emissions~~ data are provided, for each country, in both IPCC and FAO classifications. Specifically, ~~organized in~~on the one hand, data can be downloaded using 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*. Both the total emissions from IPCC sectors are provided, as well as the portion directly related to agri-food systems. ~~IPCC sectors and sub-sectors are mapped~~On the other hand, through the IPCC to FAO mapping discussed above and extending previous work (Tubiello, 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)~~categories relevant to food and agriculture, in line with recent work (Tubiello, 2021a), with extensions made to cover all IPCC sectors with relevant food systems activities (Fig. 1)~~.

~~To the extent possible, GHG emissions are accounted for~~The FAOSTAT emissions estimates follow the IPCC (2006) "territorial approach," i.e., they are assigned to ~~in~~ the countries where they~~emissions~~ occur, independently of production or consumption considerations. For example, CO_2 emissions from energy use in fertilizers manufacturing are accounted for in the producing country ~~producing fertilizers~~, while~~and~~ the N_2O emissions from ~~synthetic fertilizer~~fertilizer ~~applications~~ used on a country's agricultural land for crop production are accounted for in that countr~~yies where the fertilizer is applied~~. Similarly, ~~GHG~~ emissions from energy use in agri-food systems activities are accounted for in countries where fuel combustion for that particular activity occurs, including electricity generation~~, in accordance with IPCC methodology (IPCC, 2006)~~. 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 section 2.3.

~~The methods applied herein cover a large component of food supply chain processes. It does not cover by design embedded energy in machinery and upstream emissions associated with oil and gas supply chains.~~

2.2 Emissions Estimates

FAO regularly disseminates emissions data for fifteen sub-domains in relation to the farm gate and land use change components of agri-food systems emissions, with published methodologies and results (i.e., Tubiello et al., 2021a). This manuscript relies in addition on new methods for computing emissions from pre- and post-production processes. Specifically, methods for emissions from energy use in fertilizers manufacturing, food processing, retail and household consumption, as well as refrigeration in retail are presented in Tubiello et al,

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(2021b), while Karl and Tubiello (2021 a,b) presented methods for estimating agri-food systems emissions in transport and waste disposal. Finally, emissions from on-farm energy use were developed by Flammini *et al.*, 2021). 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 Supplementary Material ot this manuscript.

~~We provide here the basic estimation methods used for this work, while referring~~and refer ~~the interested reader to a series of technical papers that document the underlying methodologies in full, detailing all coefficients and data sources used to estimate emissions from energy use in fertilizers manufacturing, food processing, transport, retail, household consumption, waste disposal (Tubiello et al., 2021b; Karl and Tubiello, 2021a, b); as well as energy use on the farm (Flammini et al., 2021). More generally, a~~ More generally, a step-wise approach was followed for the estimation of agri-food systems emissions, as follows~~:~~

Step 1: ~~-~~identify~~ied,~~ for each food systems component, the relevant international statistics needed to characterize country-level activity data (AD);

~~-~~*Step 2*: ~~-~~determine~~d~~ the food-related shares of the activity data (AD_{food}) and assigns relevant GHG emission factors (EF) to each activity;

~~-~~*Step 3*: ~~-~~implement~~ed~~ 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:

$$E_{food} = EF*AD_{food} \qquad (1)$$

~~Finally, where country-specific activity data were lacking, Step~~ *Step 4:* ~~4~~ ~~I~~imputed ~~any~~ missing agri-food systems GHG emissions data ~~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 ~~, using as input~~ PRIMAP, a complete dataset of emissions estimates for all IPCC sectors, by country, covering the period 1990-2019 (Gütschow et al., 2021). ~~The imputations were performed by applying country-specific food system emissions shares to years with missing data, or by applying regional averages when no country-specific data is available (See Tubiello et al., 2021b for more details).~~ The PRIMAP dataset is already available in FAOSTAT for the computation of emissions shares of agriculture to the total anthropogenic total (FAO, 2019; Tubiello et al., 2021a). It ~~-~~compiles all available information on GHG emissions by country, including from official reporting. ~~They~~ It ~~wesre~~was used internationally as the basis for an early, first-order estimate of agri-food systems shares in total GHG emissions (IPCC, 2019). Additionally, ~~they were~~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). ~~The combined use of FAOSTAT and PRIMAP data presented herein is referred to as the FAOSTAT-PRIMAP dataset.~~

2.3 Global Warming Potentials Used

The estimated emissions data ~~are converted from~~expressed in CH_4methane and N_2O ~~nitrous oxide~~ gases were converted to CO_2-equivalents by using the 100-year global warming potentials (GWP) of the ~~as found in the~~ IPCC

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Fifth Assessment Report (AR5), specifically:~~, Details on conversions factors are as follows~~: ~~found as follows.~~ GWP-CH_4 = 28 ~~(100-year time horizon global warming potential~~,~~), to convert Gg CH_4 to Gg CO_2eq~~; GWP-N_2O = 265 ~~to convert Gg N_2O to Gg CO_2eq~~ (IPCC ~~AR5~~, 2014: ~~Synthesis Report, Box 3.2 Tab. 1, pg. 87~~).

2.3 Data uncertainty and limitations

2.3.1 Boundaries

~~Uncertainties in farm gate and land use change emissions estimates have been characterized elsewhere, ranging 30 – 70% across many processes (Tubiello, 2019). The uncertainties in the estimates of pre- and post-production activities described herein are less documented. On the one hand, uncertainties in underlying energy activity data and emissions factors are likely lower than for the other two components. On the other, the relative novelty in estimating food system shares for a range of activity data makes our estimates more uncertain, with heavy reliance on literature results from a subset of countries or regions that are necessarily extended to the rest of the world (Karl and Tubiello, 2021a). In addition, it should be noted that T~~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 ~~a~~ 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, ~~and likewise~~which ~~t~~itself excludes upstream GHG emissions in the fuel chain used to generate electricity (Flammini et al., 2021; Tubiello et al., 2021b).

Conversely, ~~processes such as F-gas~~ 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. ~~Furthermore~~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 ~~Insitute~~Institute of Refrigeration, 2021). ~~and estimation methods.~~ 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 fertilizers manufacturing (Brentrup et al., 2016; Brentrup et al., 2018; IFS, 2019). ~~To put the magnitude of pesticides manufacturing into perspective,~~ Bellardy et al. (2008) estimate~~ds~~ global ~~that~~ emissions from~~the~~ pesticides ~~industry accounts for approximately~~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. ~~of emissionspesticide, although this estimate was presented with a large amount of uncertainty (3-140 Mt CO2eq yr^{-1}).~~

2.3.2 Uncertainty

Uncertainties in FAOSTAT farm gate and land use change emissions estimates have been characterized elsewhere, and computed in line with IPCC (2006) guidelines as ranging 30—70% across component~~many~~ processes ~~(Tubiello, 2019)~~. In particular we assign uncertainties of 30% and 50% respectively to the farm gate and land use change components of the FAOSTAT agri-food systems emissions, following 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 known to be~~are~~ ~~likely~~ lower than for the other two components, ranging 5-20% (Flammini et al., 2022). On the

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other hand, the relative novelty in estimating food systems shares for a range of activity data across many processes makes our estimates moree uncertain, with heavy reliance on literature results from a subset of countries and~~or~~ regions that are necessarily extended to the rest of the world (Karl and Tubiello, 2021a). For this reason, we assign an uncertainty of 30% overall to the pre- and post-production component of agri-food systems, higher than the uncertainty in the underlying energy processes, yet quite in line with values used in similar 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 systems 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 ~~In particular, sSignificant errors may be introduced by the use of~~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 systems 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~~.~~

~~Uncertainties also exist in estimating GHG emission factors. These are typically related to difficulties in derive generic coefficients in the face of natural spatial and temporal variability characterizing the underlying bio-physical processes. More detailed information on uncertainties associated with emission factors and activity data can be found in the IPCC guidelines (2006)~~.

2.3.3 Areas for Advancement

Work towards estimating agri-food systems 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— 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, JRC, 2015; Pablo-Romero et al., 2017; Wang, 2014).

Data availability

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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 at: https://zenodo.org/record/5615082~~data, with DOI 10.5281/zenodo.5615082 (Tubiello et al., 2021d) and via the FAOSTAT emissions shares database (FAO, 2021a) ~~database~~.

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3 Results

3.1 Global trends

The FAOSTAT~~T-PRIMAP~~ dataset ~~which underlies~~considered in this study estimates in 2019 total anthropogenic emissions at ~~about~~ 52 Gt CO_2eq yr^{-1} without land use, land use change and forestry emissions (LULCUF), and ~~about~~ 54 Gt CO_2eq 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 systems emissions, expressed in terms of 95% confidence intervals (CI) determined using an overall uncertainty of 40%, were 16.5 (CI range: 10-23)~~6.5~~ billion metric tonnes (Gt CO_{2eq} yr^{-1}), corresponding to 31% (range: 19%-42%) of total anthropogenic emissions (Tab. 1). Of the food systems 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_{2eq} yr^{-1}; emissions from land use change, due to deforestation and peatland degradation, were 3.5 (range: 2-5) Gt CO_{2eq} 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_{2eq} yr^{-1}. Over the study period 1990-2019, agri-food systems 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 sub-components, have been discussed in Tubiello et al. (2021a) and are regularly presented within FAOSTAT statistical briefs (e.g., FAO, 2020~~0~~a; 2021b). Here we provide a detailed discussion of the components of agri-food systems 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~~,058~~ G~~M~~t CO_2 yr^{-1}, having decreased 30% since 1990. The second most important component were non-CO_2 emissions from enteric fermentation (2.~~,~~8~~23~~ G~~M~~t CO_2eq yr^{-1}), with increases of 13%. These were followed by emissions from livestock manure (1.3~~,315~~ G~~M~~t CO_2eq yr^{-1}) and several pre- and post-production emissions, including CO_2 from household consumption (1.3~~,309~~ G~~M~~t CO_2eq yr^{-1}), CH_4 from food waste disposal (1.3~~,278~~ G~~M~~t CO_2eq yr^{-1}), mostly CO_2 from fossil-fuel combustion for on-farm energy use (1.0~~,021~~ G~~M~~t CO_2eq yr^{-1}), and CO_2 and F-gases emissions from food retail (0.99~~32~~ G~~M~~t CO_2eq 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 seven-fold, while emissions from household consumption more than doubled over the same period.

Finally, while emissions from agri-food systems increased globally by 16 percent between 1990 and 2019, their share in total emissions decreased, from 40 percent to 31 percent, as did the per capita emissions, from 2.7 to 2.1 tonnes CO_2eq per capita (Fig 2.)

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3.2 Regional Trends

Our results indicate significant regional variation in terms of the composition of agri-food systems emissions by component (Fig. 4). Specifically, in terms of total agri-food systems emissions in 2019, Asia had the largest contribution, at 7 Gt CO_2eq yr^{-1}, followed by Africa (2.7 Gt CO_2eq yr^{-1}), South America (2.4 Gt CO_2eq 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_2eq yr^{-1}), followed by Europe and North America (0.8-1.1 Gt CO_2eq yr^{-1}). Regions also varied in terms of how agri-food systems components contributed to the total (Tab. 2). In 2019, pre- and post- production emissions were the largest food systems 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 they were the dominant emissions component. Since then, they doubled in all regions except in Africa—where it remained below 15%.

~~Finally,~~ T~~t~~he data show which pre- and post-production process was most important by region (Tab. 2). In 2019, food household consumption was the dominant process outside of agricultural land emissions in Asia (0.9 Gt CO_2eq yr^{-1}) and Africa (0.2 Gt CO_2eq 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_2eq yr^{-1}), while South America was dominated by emissions from food waste disposal (0.2 Gt CO_2eq 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_2eq yr^{-1}), followed by India, Brazil, Indonesia and the USA (1.2-1.3 Gt CO_2eq yr^{-1}). Democratic Republic of Congo (DRC) and Russian Federation followed with 0.5-0.6 Gt CO_2eq 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 systems 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 systems emissions. The land use contribution was also minor in the USA, 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 (Tab. 3). For the year 2019, pre- and post-production emissions were dominated in China by food household consumption processes (463 Mt CO_2eq yr^{-1}), whereas food waste disposal was the dominant pathway in Brazil, Indonesia (77 Mt CO_2eq yr^{-1}), DRC (8 Mt CO_2eq yr^{-1}), Pakistan (33 Mt CO_2eq 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_2eq yr^{-1}), Russian Federation (177 Mt CO_2eq yr^{-1}) and Canada (20 Mt CO_2eq yr^{-1}). Finally, on-farm energy use was the largest pre- and post-production component in India (205 Mt CO_2eq yr^{-1}).

4 Discussion

4.1 Comparisons with previous work

The overall assessment of total agri-food systems emissions found in this work confirms recent previous findings by the IPCC (2019) and Crippa et al. (2021). ~~As displayed in Tab. 4, the~~With regards to pre- and post-production, the FAOSTAT ~~agri-food systems emissions~~ estimates were consistent (Tab. 4) with previous findings ~~work performed by~~(i.e., ~~-~~Crippa et al., ~~(~~2021a, b; Vermuelen et al., 2012; Poore and Nemecek, 2018). In particular, ~~for~~ emissions estimates for ~~the activities of~~ food transport, processing, waste and retail were consistent with EDGAR-FOOD ~~components – considering uncertainties of about 30~~ (Karl and Tubiello, 2021b) and estimates for fertilizers manufacturing were in line with previous work by Vermeulen (2012) ~~percent in EDGAR-FOOD estimations (Crippa et al., 2021a,b)~~. Conversely~~Conversely, our methods led to~~FAOSTAT estimates were ~~significantly~~ higher than EDGAR-FOOD for~~estimates of~~ household consumption ~~emissions,~~ and ~~significantly~~ lower for ~~for~~ food packaging, the latter possibly linked to~~. For food processing, EDGAR-FOOD estimates include emissions from industrial wastewater management, which are instead accounted for separately in our approach (Karl and Tubiello, 2021b).~~

~~FAOSTAT estimates for food packaging were likewise consistently lower, often by a factor of 2–3, than published results, including Vermuelen et al. (2012) and Poore and Nemecek (2018), which nonetheless, as noted for~~FAOSTAT estimates excluding ~~EDGAR-FOOD data, included additional,~~ indirect ~~life-cycle processes~~emissions from fuel supply chains, which were instead included in previously published estimates. ~~compared to those considered in this methodology. Nevertheless, our estimates for emissions from energy use in the manufacturing of specific food system packaging materials are consistently higher than EDGAR-FOOD estimates, likely owing to differences in food share assumptions and activity data used as input (Tab. 4).~~

~~Our estimates of GHG emissions from energy use in fertilizers manufacturing were about 420 million tonnes CO_2eq in 2019, representing less than 8 percent of pre- and post-production emissions. While EDGAR-FOOD emissions from fertilizers were not available as a stand-alone component, our estimates of 325 million tonnes CO_2eq in 2007 were within the range 282–575 million tonnes CO_2eq estimated for the same year by Vermeulen *et al.* (2012), though the latter included life-cycle processes that our methods exclude by design – for instance indirect emissions from the extraction and supply of fossil fuels or from the storage and transfer of phosphorus and potassium fertilizers (Tab 4.)~~

Finally, our estimates of F-gas ~~The good agreement on e~~emissions from ~~food~~ retail ~~between FAO and~~agreed well with those published in EDGAR-FOOD.

The most important disagreement with previous work was observed ~~was largely related to F-gas emissions, which dominate this food system component total and are estimated similarly between the two approaches. Small differences on the other hand could be related to different activity data (UNSD vs. IEA energy statistics). Our estimates are consistent with specific current literature on national trends. For the~~

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~~**United Kingdom of Great Britain and Northern Ireland for instance, our estimates of the contribution of energy use in retail, about 1.5–2 percent, were consistent with those of Tassou et al. (2011).**~~

in relation to ~~The most pronounced difference between our estimates and EDGAR-FOOD was for~~ household consumption emissions~~, as our methods lead to estimated emissions in 2015 of roughly~~. FAOSTAT estimates in this work, ~~-~~1.2 Gt CO_2eq, were ~~, or~~ nearly three times those of~~e~~ EDGAR-FOOD (with reference to 2015, the last year for which EDGAR data was available)~~ values~~. While much more research is needed to refine estimates in this important agri-food systems component, our estimates were in fact well aligned with earlier FAO (2011)~~Yet, FAO~~ work ~~(2011) estimates of this food systems component in the early 2000s, of about 1.2 Gt CO_2eq, is closer to our estimates of 0.8 Gt CO_2eq for the same period, whereas EDGAR-FOOD estimates only about half that amount~~ (Figure 4~~). The trend in our estimates may be more realistic, as it properly~~), as well as more consistent with observed ~~reflects concomitant increases in world~~ population growth~~ during the study period~~, an important determinant of ~~whereas such trends are missing from the EDGAR-FOOD data. Indeed, trends in~~ household consumption trends~~should match global population growth~~. ~~For instance, global residential energy use grew by 25 percent from 1993 to 2013, while per capita use remained rather constant over the same period (Pablo-Romero et al., 2017). At the same time, major energy transitions occurred in Asia, especially rural China, where between 1992 and 2002 electricity and LPG consumption were multiplied by 97 and 7, respectively, while consumption of biomass decreased by more than 50 percent (Tao et al., 2018).~~

4.2 Trends

~~The most important~~One notable trend over the 30-year period since 1990 ~~to present that emerges from our analysis~~ 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~~scales from global, regional and national, from 1990 to 2019~~. Our data show that by 2019, ~~food supply chains~~pre- and post-production processes had overtaken farm-gate processes to become the largest GHG component of agri-food systems emissions in Annex I parties (2.2 Gt CO_{2eq} yr^{-1}). While farm gate emissions still dominated food-systems 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_{2eq} yr^{-1}. By 2019, ~~food supply chains~~pre- and post-production processes had become the largest agri-food system component in China (1.1~~,100~~ G~~M~~t CO_{2eq} yr^{-1}); USA (0.7~~00~~ G~~M~~t CO_{2eq} yr^{-1}) and EU-27 (0.6~~600~~ G~~M~~t CO_{2eq} yr^{-1}). This has important repercussions for food-relevant national mitigation strategies, such as those included in countries' NDCs, 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 systems emissions in total anthropogenic emissions, by country as well as at regional and global levels, over the period 1990-2019. ~~The FAOSTAT-PRIMAP database covering all sectors which underlies this study estimates total anthropogenic emissions at about 52 Gt CO_2eq yr^{-1} without land use, land use change and forestry emissions (LULCUF), and about 54 Gt CO_2eq yr^{-1} with LULUCF – consistently with recent estimates (IPCC, 2019). We use the latter figure to compute emissions shares.~~ A number of important issues can be highlighted to this end (Tab. ~~5~~4 and Fig. 6). First, in terms of CO2eq, the share of world total agri-food systems emissions decreased from 40% in 1990 to 31% in 2019. Thus while it is important to note that one-third of all GHG emissions

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today are generated by agri-food systems, their shares in total emissions may continue to decrease~~ing~~ in the near future. This decreasing trend was driven by trends in large regions, ~~with ongoing~~consistently with transformations in their agri-food systems and land use change patterns. For instance, in South America, the region with the highest food systems share over the entire study period (Fig. 6), food shares decreased~~went~~ 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~~ however~~, our data suggested that in regions dominated by modern agri-food systems, such as Europe and North America, ~~our data suggest that~~ the overall share of agri-food systems 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 ~~in these two regions were due to a disproportionate increase~~could be explained by increases in absolute emissions from pre- and post-production activities~~, as noted earlier, resulting in addition to doubling absolute emission also doubled their underlying shares~~ (Tab. 5~~4~~), re-enforced by concomitant~~. The phenomenon of increasing shares of agri-food systems emissions in Europe and North America may also be attributable to sustained declines in~~ emissions decreases ~~from other sectors~~in non-food sector, ~~such as~~especially ~~from~~ energy systems (Lamb et al., 2022). ~~It is also worth noting that~~The noted increase in ~~in all regions~~ absolute emissions froorm pre- and post-production activities ~~increased from 1990 to 2019~~was in fact present in all regions, leading to increases in the relative contributions to agri-food systems of this component, except for Africa~~, and that such increased in all regions but Africa were accompanied by larger relative shares of this food system component in 2019 compared to 1990~~.

An~~ final~~ analysis on agri-food systems impacts on total GHG emissions would not be complete without a focus on component gases in addition to quantities expressed in CO_2eq. The FAOSTAT data confirm the trends form 1990 to 2019 seen for total CO_2eq emissions, with important features (Tab. 6~~5~~). 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~~r~~ in Africa (52%) and South America (70%), largely in relation to~~ the~~ land use change emissions, ~~that are~~ still significant therein. ~~Additionally,~~ Europe and North America were the only regions where the CO_2 share of agri-food systems ~~s~~ 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 (Tab. 6~~5~~), linked to farm gate production processes (Tubiello, 2019).

Finally, the data highlight a very large increase in agri-food systems 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. ~~At least with respect to the underlying assumptions made in our methods, s~~Such a marked increase ~~was entirelymainly due to the~~is consistent with the growth in use of hydrofluorocarbons (HFCs) as refrigerants in the food retail and other sectors, following the banning of CFCs in 1990 ~~sector, which increased significantly after the Montreal Protocol, and have only recently begun to taper off in many places due to the Kigali Amendment to the Montreal Protocol. strong growth of refrigeration in the food retail sector~~ (Hart et al., 2020; International Institute of Refrigeration, 2021; Tubiello et al., 2021b). ~~This sharp increase reflects marked jumps in global~~Our findings are furthermore consistent with the strong growth in ~~-~~F-gas emissions reported in recent studies ~~overall, which are~~

Commented [K(18]: Response to RC 1: "Presumably it is also due to shifts in other sectors, e.g. all else equal, reductions in power sector emissions will increase the proportion of food system emissions in the total. And power sector emissions have been declining in most EU countries and the US "

~~one of the fastest-growing classes of GHG emissions~~ (Minx et al., 2021; Park et al., 2021). ~~See Crippa et al. (2021a) for a specific list of HFCs used in agri-food systems, which form the basis of the GHG emissions data estimated in this work.~~

An important~~other~~ aspect of the dataset ~~underlying~~ presented in this study is ~~that it~~its provision of~~des~~ ~~food and agriculture relevant~~ information mapped across IPCC and FAO ~~definitions and classifications~~categories alike. ~~In terms of national GHGH inventories~~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~~, it is worth pointing out that while~~ findings highlight the importance to expand that reporting to a fuller -agri-food systems view, one that properly weights the contribution of food to the global economy. ~~were found to be about~~Indeed, our results show that agri-food systems 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, ~~, *our data indicated that emissions from land use, land use change and forestry (LULUCF) in 2019*~~ *LULUCF* and *AFOLU* emissions ~~only~~ ~~represented~~contributed ~~3~~ respectively -4%~~,~~ and ~~*while emissions from agriculture, forestry and other land use (AFOLU), were*~~ ~~a mere~~ 15% of the total ~~anthropogenic emissions~~.

5 Conclusions

This paper provided details of a new FAOSTAT ~~domain~~ database ~~characterizing~~ 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 ~~identify~~ locate GHG emissions hotspots ~~across~~in agri-food systems ~~and by~~at the country, regional and global level. ~~country, helping~~ This can ~~to identify~~inform the process of desig~~i~~ning ~~areas for~~ 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~~the~~ literature— ~~but limited in terms of datasets to farm gate processes and land use change,~~ by adding ~~a wide range of additional details~~critical information on emissions from a range of pre- and post-production processes. The new data highlight the increasingly important role that ~~these~~pre- and post-production processes play in the overall ~~emissions~~ GHG footprint of agri-food systems, which may provide insight into ~~reflects~~ing ~~a pattern of development from~~ the relationship between ~~t~~agri-food system development trends and ~~GHG emissions~~future mitigation options.

~~raditional to modern agri-food systems and overall economic growth.~~ The granularity of the dataset allows, for the first time, to highlight specific processes of importance in specific countries or group 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 systems

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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 pratical '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.

6. Disclaimer

The views expressed in this paper are the authors' only and do not necessarily reflect those of FAO, UNSD, UNIDO and IEA.

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TABLES

~~Process~~ ~~Agri-Food System~~ Activity	~~Agri-Food System~~ Category	1990	2019	Change
Net Forest conversion	Land Use Change	4,392	3,058	-30%
Enteric Fermentation	Farm-Gate	2,494	2,823	13%
Livestock Manure	Farm-Gate	1,101	1,315	19%
Household Consumption	Pre- and Post-Production	541	1,309	142%
Waste Disposal	Pre- and Post-Production	984	1,278	30%
On-farm energy use	Farm-Gate	757	1,021	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%
Fertilizers 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	N/A	-3,391	-2,571	-24%

Table 1. GHG emissions (Mt CO_2eq) by agri-food systems 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.

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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

Table 2. Regional GHG emissions (Gt CO_2eq) by agri-food systems component, showing farm gate, land use change (LUC), pre- and post-production processes (PPP) and total emissions P~~total food systems emissions and p~~ercentage contribution of ~~emissions form~~PPP shown ~~pre- and post-production processes~~for the year ~~.~~1990 and 2019. The last two columns show the largest estimated ~~sub-component~~contributing PPP activity ~~of pre- and post-production emissions~~ by region. Uncertainties are estimated to be 30% for farm gate and PPP activities, 50% for land use change.

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

Table 3. Top ten country GHG emissions (M~~G~~t CO_2eq) by agri-food systems component and total food systems 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 ~~when summed~~. Country level uncertainties those used for global and regional estimates.

Food system component	**FAO (2011)[1]**	**Vermeulen *et al.* (2012)[2]**	**Poore & Nemecek (2018)[3]**	**Ritchie (2019)[4]**	**Tubiello *et al.* (2021a)[5]**	**Crippa *et al.* (2021) 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		0.2	0.6	0.5		0.5	0.5
Food packaging	2.1	0.4	0.6	0.7	4.3 (incl. retail and household consumption)	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 4. Overview of pre- and post-food production GHG emission estimates from selected studies, Gt CO2eq. Adapted from Tubiello et al. (2021b).

	Farm gate		Land Use Change		~~Supply Chains~~Pre- and Post-Production		Agri-f~~F~~ood Systems Total	
	1990	2019	1990	2019	1990	2019	1990	2019
Africa	705	1139	1017	1220	323	388	2045	2747
	23%	24%	33%	26%	11%	8%	67%	57%
Asia	2595	3250	1273	865	1223	2930	5091	7044
	25%	11%	12%	3%	12%	10%	49%	24%
Europe	1603	854	88	83	589	1140	2280	2077
	16%	13%	1%	1%	6%	17%	23%	31%
North America	538	574	175	156	376	777	1089	1507
	8%	8%	3%	2%	6%	11%	17%	21%
South America	728	982	1974	1106	176	281	2878	2369
	23%	30%	64%	34%	6%	9%	93%	72%
Oceania	267	223	65	16	42	71	374	309
	40%	28%	10%	2%	6%	9%	57%	39%
World	6604	7214	4676	3503	2886	5827	14165	16544
	19%	13%	13%	6%	8%	11%	40%	31%

Table 54. Regional GHG emissions (M~~G~~t CO_2eq) by agri-food systems component and total food systems 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.

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	CO$_2$eq		CO$_2$		CH$_4$		N$_2$O		F-gases	
	1990	*2019*	*1990*	*2019*	*1990*	*2019*	*1990*	*2019*	*1990*	*2019*
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

Table 65. World total and regional GHG agri-food systems emissions shares (%), 1990~~2019~~-2019, by~~for all~~ single gas~~GHG~~ and ~~in~~ 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 HFCs used in agri-food systems, which form the basis of the F-gas~~GHG~~ emissions data estimated in this work.

FIGURE LEGENDS

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

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, 2021). Also shown are emissions per capita (authors' own calculations).

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, 2021).

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, 2021).

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Figure 5. Total GHG emission from agri-food systems by country, top ten 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, 2021).

Figure 6. Top panel: Agri-food sytems emissions ($GtCO_2eq\ yr^{-1}$); Bottom panel: shares of agri-food systems in total anthropogenic emissions (%). Data shown by region, 1990-2019. Color bars show contributions component: farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: FAOSTAT (FAO, 2021).

IPCC		Food Systems Activity	GHG: CH_4	N_2O	CO_2	FAO		
AFOLU	LULUCF	Net Forest Conversion	x	x	x	LAND USE CHANGE		FOOD SYSTEMS
AFOLU	LULUCF	Tropical Forest Fires	x	x	x	LAND USE CHANGE		FOOD SYSTEMS
AFOLU	LULUCF	Peat Fires	x		x	LAND USE CHANGE		FOOD SYSTEMS
AFOLU	LULUCF	Drained Organic Soils	x		x	FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Burning - Crop residues	x	x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Burning - Savanna	x	x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Crop Residues		x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Drained Organic Soils		x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Enteric Fermentation	x			FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Manure Management	x	x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Manure Applied to Soils		x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Manure Left on Pasture		x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Rice Cultivation	x			FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
AFOLU	AGRICULTURE	Synthetic Fertilizers		x		FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
ENERGY		On-farm Energy Use	x	x	x	FARM GATE	AGRICULTURAL LAND	FOOD SYSTEMS
ENERGY		Transport	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
ENERGY		Processing	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
ENERGY		Packaging	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
ENERGY		Fertilizer manufacturing	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
ENERGY		Household consumption	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
ENERGY		Retail –Energy Use	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
Industry		Retail –Refrigeration	x	x	x	PRE AND POST PRODUCTION		FOOD SYSTEMS
WASTE		Solid Food Waste	x			PRE AND POST PRODUCTION		FOOD SYSTEMS
WASTE		Incineration			x	PRE AND POST PRODUCTION		FOOD SYSTEMS
WASTE		Industrial Wastewater	x	x		PRE AND POST PRODUCTION		FOOD SYSTEMS
WASTE		Domestic Wastewater	x	x		PRE AND POST PRODUCTION		FOOD SYSTEMS

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

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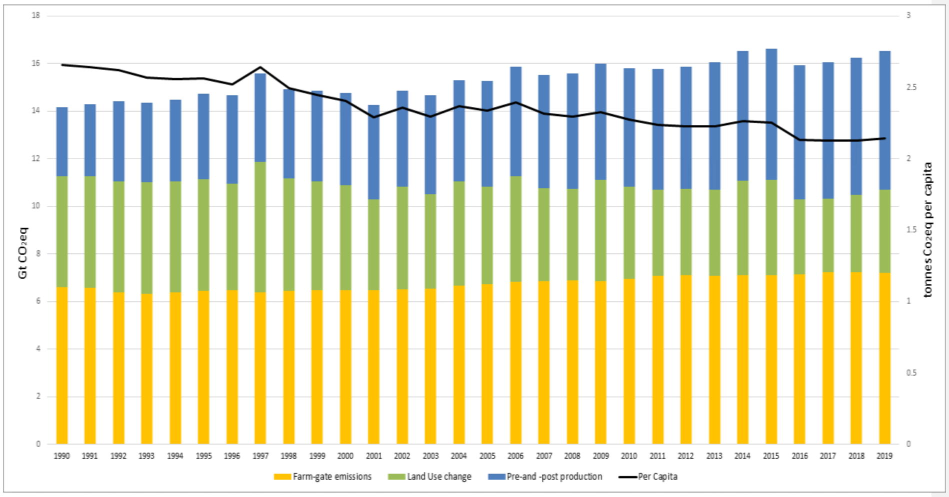

Figure 2. World-total GHG emissions from agri-food systems, 1990-2019. Color bars show contributions by emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: FAOSTAT (FAO, 2021). Also shown are emissions per capita (authors'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

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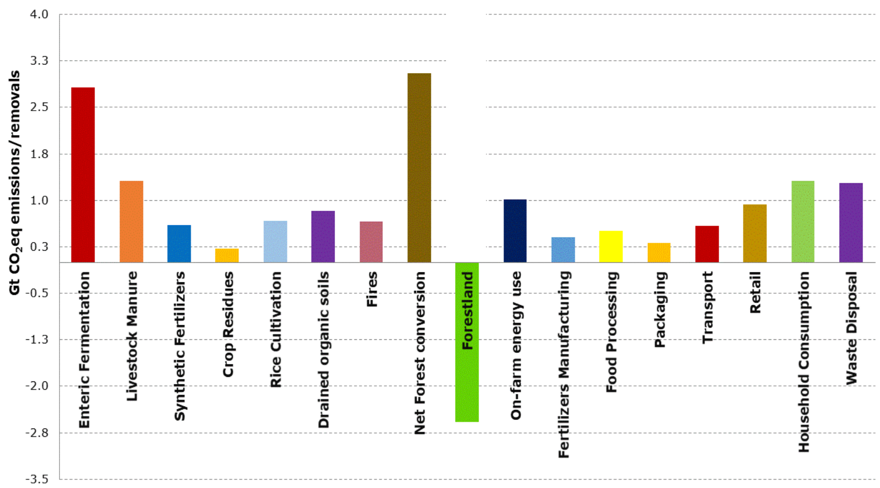

Figure 3. World total 2019 GHG emission from agri-food systems. ~~, showing C~~Contributions on agricultural land are displayed on the left, ~~(left panel)~~ and from pre- and post- production along food supply chains on the right. ~~(right panel).~~ Net removals on forest land are also shown in the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

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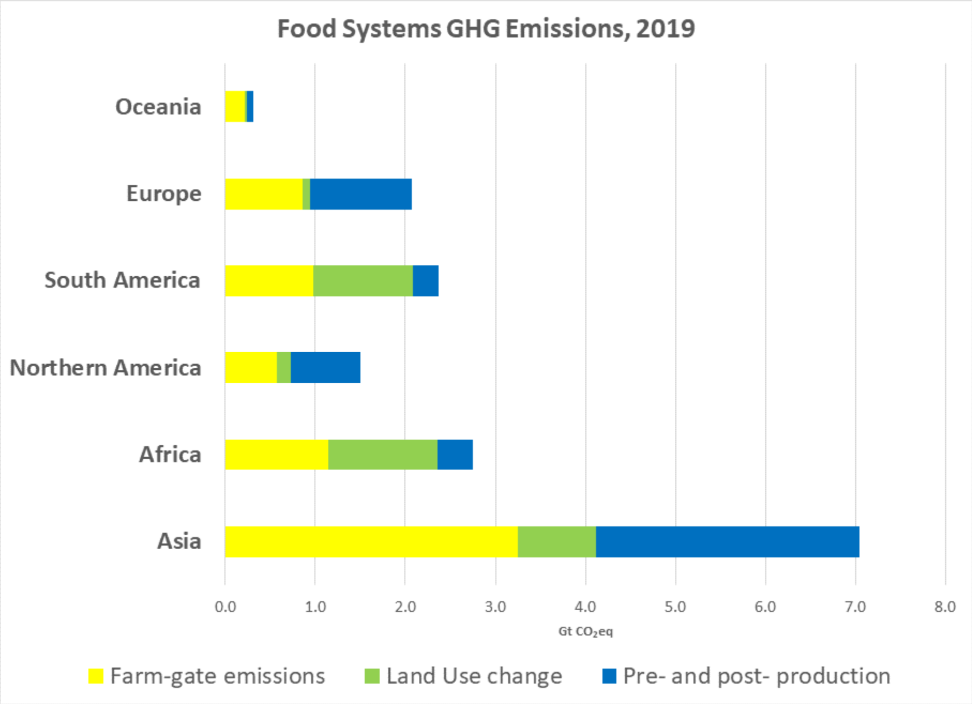

Figure 4. Total GHG emission from agri-food systems by FAO regions, 2019. Color bars show contributions by emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: FAOSTAT (FAO, 2021).

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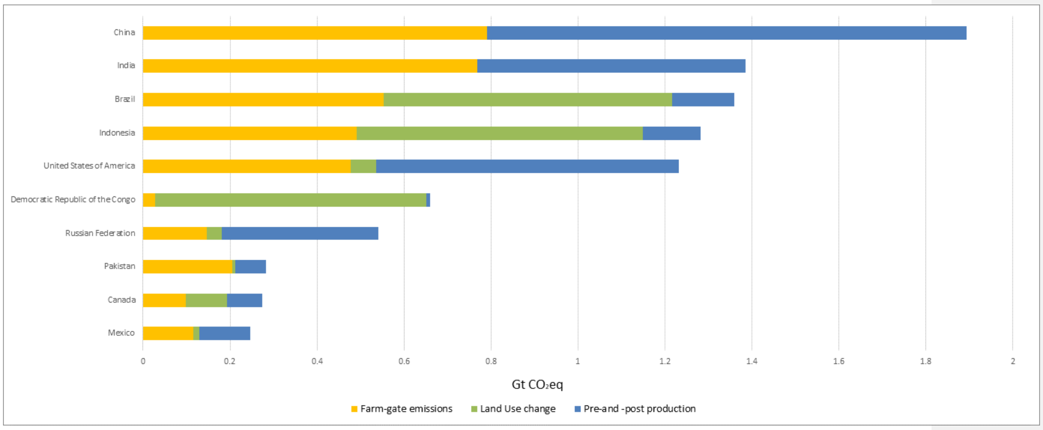

Figure 5. Total GHG emission from agri-food systems by country, top ten emitters, 2019. Color bars show contributions by emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: FAOSTAT (FAO, 2021).

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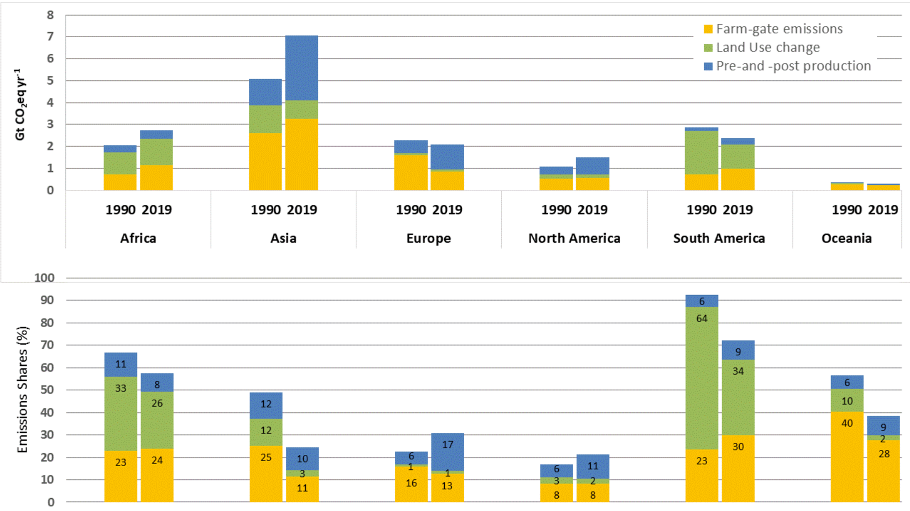

Figure 6. Top panel: Agri-food systems emissions (GtCO$_2$eq yr^{-1}). ~~;~~ Bottom panel: shares of agri-food systems in total anthropogenic emissions (%). Data shown by region, 1990-2019. Color bars show contributions component: farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: FAOSTAT (FAO, 2021).

~~CC1:~~

~~Question rather than comment. Layman's question at that - apologies in advance... I'm struggling with the amount of stuff published on FALU/food, agriculture and food systems! A simple question I came across a stat that 80% of agricultural emissions (so not food supply) come from meat, dairy and rice - is this correct? Next what is your estimate of FALU only emissions currently i.e. land use change, agriculture, farming, livestock and crops. Thank you.~~

~~RC1:~~

~~Overall this is an important contribution, updating one of the major datasets on global food system emissions. However the manuscript requires further work to make transparent key assumptions and issues with the data (scope and uncertainty), while the dataset itself is not sufficiently user friendly and appropriately documented in its current form. Nevertheless, I strongly support this effort and congratulate the authors on their work.~~

~~Page 1~~

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~~Line 28: is it FAO or FAOSTAT (line 20)?~~

~~Line 30: "in terms of single GHG" change to "in terms of individual greenhouse gases (GHGs)"~~

~~Line 34: the time period (1990-2019) is mentioned twice, at the beginning and end of the sentence~~

~~-~~

~~Page 3~~

~~Line 2: typo in the first sentence, should read "as well as one of the economic sectors most at risk from it"~~

~~Line 8: EDGAR-FOOD would be another important reference to include in this sentence (https://www.nature.com/articles/s43016-021-00225-9)~~

~~-~~

~~Page 4~~

~~Line 31: typo in 2022-2023~~

~~Line 35- page 5 line 4: These sentences belong in the subsequent section on uncertainty.~~

~~-~~

~~Page 5~~

~~Line 5-11: Can the authors restructure to make a clear distinction between emissions sources that are (a) not included because they are indirect and out of scope ("upstream GHG emissions, refining, etc.") and (b) not included because data was not available, even though they are direct and within scope?~~

~~It would be important to note in (a) whether or not indirect emissions from electricity use are also excluded, as this is generally the largest indirect source across all sectors; and in (b) how significant these sources are in estimated CO2 equivalents, and whether this is a complete list of omitted direct emissions sources.~~

~~-~~

~~Line 12-21: This is a relatively short discussion of uncertainty – given its importance in the context of food system emissions. As stated above, several sentences from the prior section could be brought down. Several further points could be made:~~

Commented [KK19]: Should be FAOSTAT right?

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Commented [KK20]: Addressed.

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Commented [KK21]: Addressed.

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~~Does the estimated uncertainty range ("30 – 70% across many processes (Tubiello, 2019)") also hold true for this dataset? Please be explicit.~~

~~Could uncertainty estimates be provided for sub-components of the data (e.g. by gas, or food system component)? This is critical information for the data users.~~

~~To what extent does uncertainty prevent us from making policy relevant statements on (1) total emissions levels, (2) total emissions trends, (3) the relative importance and impact of different food system components?~~

~~Does uncertainty increase with decreasing scale (global to regional to country level data)?~~

-

~~Page 6~~

~~Line 7: Perhaps state the denominator here too (total global GHG emissions) and its source? It is also not in Table 1. (I see that it appears in the discussion. Please move up here.) You might consider placing it in the abstract too, since the sentence appears there too.~~

~~Line 7: What would be the emissions range for the global total (± xGtCO2eq yr-1), given the previously stated uncertainty?~~

-

~~Page 8~~

~~Line 2-4: This is an important claim, also in the abstract. Can it be sourced? What is the measure of "national mitigation strategies"? Sector based targets within NDCs?~~

~~Line 17-22: Presumably it is also due to shifts in other sectors, e.g. all else equal, reductions in power sector emissions will increase the proportion of food system emissions in the total. And power sector emissions have been declining in most EU countries and the US (e.g. https://www.tandfonline.com/doi/full/10.1080/14693062.2021.1990831)~~

~~Line 37: The result on F-gases is surprising – and interesting. Can the authors provide a little more detail? Which are the main gases? Perhaps a link could be made to Minx et al. 2021, which corroborates F-gas growth in inventories with atmospheric inversions (Fig 2 https://essd.copernicus.org/articles/13/5213/2021/essd-13-5213-2021.html) Also, in Table 5, F-gases were 0 in 1990. Is this a data artefact? Or is it due to Montreal gases being replaced by HFCs/PFCs in the intervening decades?~~

-

~~Page 9~~

~~Line 1-6: The language here suggests these subcomponents are trivial sources ("only", "mere"). Arguably 15% or even 3-4% is not trivial, so I would simply present the numbers without inferring their importance. If one wants to make a normative point, I would argue that all emissions sources should be considered important and worth policy attention.~~

~~Line 12-32: There are multiple typos and phrasing errors here that could be improved. Please carefully check. Please also consider splitting this long paragraph into smaller chunks each with a substantive point.~~

-

~~Other comments on the manuscript:~~

~~Table 1: Could headings be added to group these sources into their higher level categories, e.g. as in Figures 1 and 2?~~

~~Table 3: You could add the fraction of global food system emissions that the top 10 add up to, in the caption.~~

~~What global warming potentials are applied to estimate GHG emissions in CO2eq?~~

-

~~Comments on the dataset:~~

~~My first impression is that the dataset is too large (200mb), unstructured, and lacking important metadata. Together these make it only available for advanced users. Some specific comments:~~

~~If one opens the .csv in Excel, a warning comes up that the data is not fully loaded (too many rows). Could it be split into several files? Or could a basic user-friendly excel version be provided alongside the raw csv file, perhaps for a useful series of aggregates (e.g. global emissions by food system component, by gas, by region/country), or the full data just for high emitters/regions? Such simplified sheets would presumably be important to assist national agricultural ministries to better understand emissions along the supply chain (a claim in the manuscript).~~

~~There is no explanation of the column headings embedded in the file (What are the flags? What are the codes? Are two codes for years really needed?). For example, a basic user wouldn't know that Area contains both countries and regions, and Element contains two separate variables for five different gases (I would personally split this in two and have a gas column).~~

~~There are no country ISO codes, which raises barriers to joining other datasets (e.g. population, gdp).~~

~~Most tricky: what is the hierarchy and structure of the "Item" column? If I filter by "World", "2019", and "Emissions (CO2eq) (AR5)", the sum of Value is 228 GtCO2eq. So there is double counting among the Items. Which items do I exclude to produce the number in the manuscript – 16.5 GtCO2eq? I see already that "Energy" is included (37GtCO2eq) and shouldn't be. How do I know which items are in and which are out of the food system account? Could you add a column for this, so we don't have to use complicated string operations?~~

~~Can we have the GHGs in native units, so that different global warming potential metrics can be applied? (Or conversely, a column with the applied AR5 GWPs)?~~

~~**Citation**: https://doi.org/10.5194/essd-2021-389-RC1~~

~~RC2:~~

~~The dataset is of interest but the methodology and underlying data is not described in the article. It is described in FAO Statistics Working Paper Series working papers, but it is not acceptable to have the methodology central in the data setting not described in the article (or in other peer reviewed articles). In particular, those methodologies are supposed to be peer reviewed, and also available (possibly as supplementary material) with a reviewed article. The methodologies from those working papers can be shortened, but upon reading them it seems that simply copying over most of the information, maybe with a summary in the main paper and a development in a supplementary material, or all in the main paper depending on the style of the review would be good as they are well written and describe adequately the methodologies. Another reason to bring those in the article is that there may be some additional peer review comments based on those methodologies.~~

~~It is somewhat unclear if additional data should be provided along with the main dataset. For instance shares of the food system. However this cannot really be discussed if the underlying methodology is not presented and discussed.~~

~~Most of the informations and the data corresponds to an already existing article, Tubiello et al., 2021a "Greenhouse gas emissions from food systems: building the evidence base". Therefore I am not sure about originality, but it may be normal as here the dataset is the focus. It makes all the more important to describe the methodology in the data article as it would be some originality.~~

~~The dataset combines different and incompatible disaggregations and nomenclatures, which is an interesting and important point of the methodology. There is an explanation of the relationships between the nomenclatures in figure 1, and in the https://zenodo.org/record/5615082 page. It is badly explained in the article, only very briefly in 2.1, although describing the data should be important in the article.~~

~~For the general public, as the dataset combines different and incompatible disaggregations and nomenclatures it is not clear if it would be of interest. Although it is important to have those informations to understand the methodology and how these data can be derived from the PRIMAP data based on the IPCC nomenclature, for a non specialist this makes a very unclear dataset.~~

~~A comparison with Crippa et al would also be welcome as it is a similar work with care to explain what is exactly the ame when crippa et al has been used as a source. It is already done adequately, as far as I can tell from my readings in the Working Paper Series working papers, but it should be in the peer reviewed article and may trigger additional comments here.~~

~~More remarks~~

~~p 4 l 33 and following, the discussion about uncertainty does not add much information, all the information is quite generic. There is some validation done in the FAO Statistics Working Paper Series articles, theis should be presented/discussed here.~~

~~p 4 l 25 The Step 4 of imputation of missing emissions is not clear (missing how?). It should be associated with additional data showing which data is imputed and which data is not.~~

~~p 6 l 35 3.2 Regional Trends~~

~~The numbers per regional blocks or countries are not very interesting as the populations may be very different. Also some goods may be exported which makes these numbers also difficult to interpret. Some emissions are directly linked with the consumption, so should be local, but it is not the case for processing, packaging and fertilizer production.~~

~~p 8 l 7 the database FAOSTAT-PRIMAP is not introduced before nor really presented. It should be presented and even be available with this data, as if I understand well it is the data which corresponds to the methodology, the data presented is an aggregation.~~

-

~~A minor remark, since the data is about reorganizing disaggregated data in different categories, the comparison of nomenclatures can be of interest in term of methodology to understand the strength and limitations of each nomenclature and warn about uses. However, this is not done at all in the article.~~

~~**Citation**: https://doi.org/10.5194/essd-2021-389-RC2~~