



1 Pre- and post-production processes along supply chains

2 increasingly dominate GHG emissions from agri-food systems

3 globally and in most countries

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       Abstract. We present results from the FAOSTAT agri-food systems emissions database, relative to 236 countries
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       and territories and over the period 1990-2019. We find that in 2019, world-total food systems emissions were 16.5
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       billion metric tonnes (Gt CO<sub>2eq</sub> yr<sup>-1</sup>), corresponding to 31% of total anthropogenic emissions. Of the agri-food
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       systems total, global emissions within the farm gate -from crop and livestock production processes including on-
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       farm energy use-were 7.2 Gt CO2eq yr-1; emissions from land use change, due to deforestation and peatland
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       degradation, were 3.5 Gt CO<sub>2eq</sub> yr<sup>-1</sup>; and emissions from pre- and post-production processes -manufacturing of
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       fertilizers, food processing, packaging, transport, retail, household consumption and food waste disposal-were
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       5.8 Gt CO<sub>2eq</sub> yr<sup>-1</sup>. Over the study period 1990-2019, agri-food systems emissions increased in total by 17%, largely
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       driven by a doubling of emissions from pre- and post-production processes. Conversely, the FAO data show that
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       since 1990 land use emissions decreased by 25%, while emissions within the farm gate increased only 9%. In
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       2019, in terms of single GHG, pre- and post- production processes emitted the most CO<sub>2</sub> (3.9 Gt CO<sub>2</sub> yr<sup>-1</sup>),
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       preceding land use change (3.3 Gt CO<sub>2</sub> yr<sup>1</sup>) and farm-gate (1.2 Gt CO<sub>2</sub> yr<sup>1</sup>) emissions. Conversely, farm-gate
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       activities were by far the major emitter of methane (140 Mt CH_4 yr<sup>1</sup>) and of nitrous oxide (7.8 Mt N_2O yr<sup>1</sup>). Pre-
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       and post- processes were also significant emitters of methane (49 Mt CH<sub>4</sub> yr<sup>-1</sup>), mostly generated from the decay
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       of solid food waste in landfills and open-dumps. The most important trend over the 30-year period since 1990
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       highlighted by our analysis is the increasingly important role of food-related emissions generated outside of
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       agricultural land, in pre- and post-production processes along food supply chains, at all scales from global, regional
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- 1 and national, from 1990 to 2019. In fact, our data show that by 2019, food supply chains had overtaken farm-gate
- 2 processes to become the largest GHG component of agri-food systems emissions in Annex I parties (2.2 Gt CO_{2eq}
- 3 yr^{-1}). They also more than doubled in non-Annex I parties (to 3.5 Gt CO_{2eq} yr⁻¹), becoming larger than emissions
- 4 from land-use change. By 2019 food supply chains had become the largest agri-food system component in China
- 5 (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
- 6 for food-relevant national mitigation strategies, considering that until recently these have focused mainly on
- 7 reductions of non-CO₂ gases within the farm gate and on CO₂ mitigation from land use change. The information
- 8 used in this work is available as open data at: <u>https://zenodo.org/record/5615082</u> (Tubiello et al., 2021d). It is also
- 9 available to users via the FAOSTAT database (FAO, 2021a), with annual updates.
- 10 Keywords: Agri-food systems, GHG emissions, farm gate, land use change, supply chains





1 1. Introduction

2 Agriculture is a significant contributor to climate change as well as the economic sectors most at risk from it. 3 Greenhouse gas (GHG) emissions generated within the farm gate by crop and livestock production and related 4 land use change contribute about one-fifth to one-quarter of total emissions from all human activities, when 5 measured in CO₂ equivalents (Mbow et al., 2019; Smith et al., 2014; Vermeulen et al., 2012). In terms of single 6 gases, impacts are even starker. Agriculture contribute nearly 50% of world total anthropogenic methane (CH₄) 7 and 75% of the total nitrous oxide (N₂O) emissions (FAO, 2021b; Gütschow et al., 2021; Saunois, et al., 2020). 8 Once pre- and post-production activities along agri-food systems supply chains are included, food and agriculture 9 activities generate up to one-third of all anthropogenic emissions globally (Rosenzweig et al., 2020; Tubiello et 10 al., 2021a). This larger food systems perspective expands the potential for designing GHG mitigation strategies 11 that can address options in food and agriculture across the entire food system, i.e., over and above the more 12 traditional focus on agricultural production and land use management within countries' Nationally Determined 13 Contributions (FAO, 2019).

14 Significant progress has recently resulted in the development of novel databases with global coverage of country-15 level data on agri-food systems emissions (Crippa et al., 2021a,b; Tubiello et al., 2021a). Tubiello et al. (2021a) in 16 particular provided a mapping of emission categories of the Intergovernmental Panel on Climate Change (IPCC), 17 used for climate reporting by countries of national GHG inventories (NGHGI), to more relevant food and 18 agriculture concepts that, developed by FAO and used to disseminate food and agriculture statistics in FAOSTAT, 19 are more easily understood by farmers and planners in Ministries of Agriculture. Such mapping allows to more 20 adequately capture important aspects of food and agriculture activities within existing climate reporting. Firstly, it 21 expands the IPCC "agriculture" definition to include, in addition to non-CO₂ emissions from the farm, also the 22 CO₂ generated in drained peatlands on agricultural land (Conchedda and Tubiello, 2020; Drösler et al., 2014) and 23 through energy use in farm operations (FAO, 2020b; Flammini et al., 2021; Sims and Flammini, 2014). Secondly, 24 it usefully disaggregates the 'Land Use, land use change and forestry' (LULUCF) of IPCC (2003) used in NGHGI, 25 by separating out carbon sinks from land-based emissions sources that are more directly linked to food and 26 agriculture, such as those generated by deforestation (Curtis et al., 2020; Tubiello et al., 2021c) and peat fires 27 (Prosperi et al., 2020).

28 We present and discuss results from the first emissions database in FAOSTAT of food and agriculture emissions. 29 The new database covers, as in previous versions (Tubiello et al., 2013) agriculture production activities within 30 the farm gate and associated land use and land use change emissions on agricultural land. Importantly, it also 31 includes estimates of emissions from pre- and post-production processes along food supply chains, including: 32 energy use within the farm gate, food processing, domestic and international food transport, retail, packaging, 33 household consumption and food waste disposal. The new FAOSTAT database provides information of emissions 34 of the four main GHG gases CO₂, CH₄, N₂O and F-gases, as well as their combined CO₂eq levels, by country, over 35 the period 1990-2019. We examine new results and discuss how they can inform national mitigation strategies that 36 are relevant to food and agriculture in countries, regionally and globally.

37 2. Materials and methods

38 Recent work (Rosenzweig et al., 2021; Tubiello et al., 2021a) helped characterize agri-food systems emissions into

39 three components: 1) Farm Gate; 2) Land Use Change; and 3) Pre- and Post-Production. Emissions estimates from





1 the first two—generated by crop and livestock production activities within the farm gate and by the conversion of

- 2 natural ecosystems to agriculture, such as deforestation and peatland degradation—have been long established and
- 3 data are regularly disseminated in FAOSTAT (FAO, 2021; Tubiello, 2019). This paper adds emission along food
- 4 supply chains outside of agricultural land, including those generated from energy use in fertilizer manufacturing;
- 5 food processing; packaging; transport; retail; household consumption; and waste disposal.

6 2.1 Mapping Agri-food Systems Components

Emissions data are organized in 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*. IPCC sectors and sub-sectors are mapped to FAO 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). 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.

13 2.2 Emissions Estimates

14 We provide here the basic estimation methods used for this work, while referring the interested reader to a series 15 of technical papers that document the underlying methodologies in full, detailing all coefficients and data sources 16 used to estimate emissions from energy use in fertilizers manufacturing, food processing, transport, retail, 17 household consumption, waste disposal (Tubiello et al., 2021b; Karl and Tubiello, 2021a, b); as well as energy use 18 on the farm (Flammini et al., 2021). More generally, a step-wise approach was followed for the estimation of agri-19 food systems emissions: Step 1 identified, for each food systems component, the relevant international statistics 20 needed to characterize country-level activity data (AD). Step 2 determined the food-related shares of the activity 21 data (AD_{food}) and assigns relevant GHG emission factors (EF) to each activity. Step 3 implemented the generic 22 IPCC method for estimating GHG emissions (E_{food}), using inputs of activity data and emission factors from the 23 first two steps, as follows:

24

$$E_{food} = EF^*AD_{food} \tag{1}$$

25 Finally, Step 4 imputed any missing agri-food systems emissions data by component, using as input PRIMAP, a 26 complete dataset of emissions estimates for all IPCC sectors, by country, covering the period 1990-2019 27 (Gütschow et al., 2021). The PRIMAP data compile all available information on GHG emissions by country, 28 including from official reporting. They were used internationally as the basis for an early, first-order estimate of 29 agri-food systems shares in total GHG emissions (IPCC, 2019). Additionally, they were recently used in a 30 UNFCCC Synthesis Report (UNFCCC, 2021) to assess world GHG emissions from all sectors in preparation of a 31 stock take exercise that will be undertaken in 2022-203 to assess countries' performance against their mitigation 32 commitments under the Paris Agreement.

33 2.3 Data uncertainty and limitations

34 2.3.1 Boundaries

35 Uncertainties in farm gate and land use change emissions estimates have been characterized elsewhere, ranging

- 36 30—70% across many processes (Tubiello, 2019). The uncertainties in the estimates of pre- and post-production
- 37 activities described herein are less documented. On the one hand, uncertainties in underlying energy activity data





1 and emissions factors are likely lower than for the other two components. On the other, the relative novelty in 2 estimating food system shares for a range of activity data makes our estimates more uncertain, with heavy reliance 3 on literature results from a subset of countries or regions that are necessarily extended to the rest of the world (Karl 4 and Tubiello, 2021a). In addition, it should be noted that the processes covered herein do not span all processes 5 attributable to agri-food systems. In particular, the scope of this work does not include, by design, upstream GHG 6 emissions in the fuel chain, such as petroleum refining, as well as a methane leaks during extraction processes and 7 piping. These are expected to be not negligible if considered. Conversely, processes such as F-gas emissions from 8 household refrigeration and from climate-controlled transportation were not included for lack of available country-9 level data and estimation methods. Emissions from pesticide manufacturing were also not included due to the 10 paucity of information and methodologies for their estimation, in contrast to advanced work in fertilizers 11 manufacturing (Brentrup et al., 2016; Brentrup et al., 2018; IFS, 2019)

12 2.3.2 Uncertainty

Significant errors may be introduced by the use of sub-regional and regional coefficients, given the diversity in 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).

22 2.3.3 Areas for Advancement

23 Work towards estimating agri-food systems emissions at the country level can be advanced in several ways. The 24 present approach could be expanded on by including other country- and region-specific studies that estimate trends 25 in energy consumption across a range of similar activities as proxies- whether or not they are distinctly related 26 to food. Furthermore, other data sources could help explain and estimate variations in agri-food systems between 27 countries, such as: GDP per capita, urbanization levels, proxies for infrastructure and industrial development, and 28 geographic and climate considerations. The development of a methodology to estimate emissions from pesticides 29 could be explored, as it would help complement the understanding of emissions associated with chemical use in 30 agriculture, in addition to fertilizers. Emissions from machinery manufacturing and from upstream GHG emissions 31 in the fuel chain could also be added to further refine the analysis. This work could be further expanded by focusing 32 on specific food commodities— requiring an additional focus on international trade and on supply and demand 33 patterns (Dalin and Rodríguez-Iturbe, 2016). Such analysis would ultimately enable consumers to understand the 34 full carbon footprint of particular commodities across global supply chains, which can facilitate GHG mitigation 35 actions taken at the consumer level (Poore and Nemecek, 2018). Furthermore, it would be also useful to further 36 investigate the increasing role of bioenergy and renewables as important mitigation opportunities in the food sector 37 (Clark et al., 2020, JRC, 2015; Pablo-Romero et al., 2017; Wang, 2014).



1 Data availability

- 2 The GHG emission data presented herein cover the period 1990-2019, at the country level, with regional and global
- 3 aggregates. They are available as open data at: https://zenodo.org/record/5615082 (Tubiello et al., 2021d) and via
- 4 the FAOSTAT (FAO, 2021a) database.

5 3 Results

6 3.1 Global trends

7 In 2019 world-total agri-food systems emissions were 16.5 billion metric tonnes (Gt CO_{2eq} yr⁻¹), corresponding to 8 31% of total anthropogenic emissions (Tab. 1). Of the food systems total, global emissions within the farm gate -9 from crop and livestock production processes including on-farm energy use-were 7.2 Gt CO_{2eq} yr⁻¹; emissions 10 from land use change, due to deforestation and peatland degradation, were 3.5 Gt CO_{2eq} yr⁻¹; and emissions from 11 pre- and post-production processes -manufacturing of fertilizers, food processing, packaging, transport, retail, 12 household consumption and food waste disposal-were 5.8 Gt CO_{2eq} yr¹. Over the study period 1990-2019, agri-13 food systems emissions increased in total by 17%, though they have remained rather constant since about 2006 14 (Fig. 2). These trends were largely driven by a doubling of emissions from pre- and post-production processes, 15 while land use emissions decreased by 25% and farm gate increased only 9%. In terms of single GHG, pre- and 16 post- production processes emitted the most CO₂ (3.9 Gt CO₂ yr⁻¹) in 2019, preceding land use change (3.3 Gt CO₂ 17 yr⁻¹) and farm-gate (1.2 Gt CO₂ yr⁻¹) emissions. Conversely, farm-gate activities were by far the major emitter of 18 methane (140 Mt CH₄ yr⁻¹) and of nitrous oxide (7.8 Mt N₂O yr⁻¹). Pre-and post- processes were also significant 19 emitters of methane (49 Mt CH4 yr⁻¹), mostly generated from the decay of solid food waste in landfills and open-20 dumps.

21 Emissions from within the farm gate and those due to related land use processes, including details of their sub-22 components, have been discussed in Tubiello et al. (2021a) and are regularly presented within FAOSTAT statistical 23 briefs (e.g., FAO, 2020a). Here we provide a detailed discussion of the components of agri-food systems emissions 24 from pre- and post-production activities along supply chains and their relative contribution to the food system 25 totals (Fig. 3). Our data show that in 2019 emissions from deforestation were the single largest emission 26 component of agri-food systems, at 3,058 Mt CO₂ yr¹, having decreased 30% since 1990. The second most 27 important component were non-CO₂ emissions from enteric fermentation (2,823 Mt CO₂eq yr⁻¹), with increases of 28 13%. These were followed by emissions from livestock manure (1,315 Mt CO2eq yr⁻¹) and several pre- and post-29 production emissions, including CO₂ from household consumption (1,309 Mt CO₂eq yr⁻¹), CH₄ from food waste 30 disposal (1,278 Mt CO₂eq yr⁻¹), mostly CO₂ from fossil-fuel combustion for on-farm energy use (1,021 Mt CO₂eq 31 yr⁻¹), and CO₂ and F-gases emissions from food retail (932 Mt CO₂eq yr⁻¹). Importantly, our data show that growth 32 in pre- and post-production components was particularly strong, with emissions from retail increasing from 1990 33 to 2019 by more than seven-fold, while emissions from household consumption more than doubled over the same 34 period.

35 3.2 Regional Trends

36 Our results indicate significant regional variation in terms of the composition of agri-food systems emissions by

- 37 component (Fig. 4). Specifically, in terms of total agri-food systems emissions in 2019, Asia had the largest
- 38 contribution, at 7 Gt CO₂eq yr⁻¹, followed by Africa (2.7 Gt CO₂eq yr⁻¹), South America (2.4 Gt CO₂eq yr⁻¹) and





1 Europe (2.1 Gt CO₂eq yr⁻¹). North America (1.5 Gt CO₂eq yr⁻¹) and Oceania (0.3 Gt CO₂eq yr⁻¹) were the smallest

- 2 emitters among regions (Fig. 4). Focusing on GHG emissions beyond agricultural land, pre- and post-production
- 3 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
- 4 CO₂eq yr⁻¹). Regions also varied in terms of how agri-food systems components contributed to the total (Tab. 2).
- 5 In 2019, pre- and post- production emissions were the largest food systems contributor in Europe (55%), North
- 6 America (52%) and Asia (42%). Conversely, they were smallest in Oceania (23%), Africa (14%) and South
- 7 America (12%). Additionally, the contribution of pre- and post-production processes along food supply chains
- 8 significantly increased since 1990, when in no region they were the dominant emissions component. Since then,
- 9 they doubled in all regions except in Africa—where it remained below 15%.

Finally, the 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 CO₂eq yr⁻¹) and Africa (0.2 Gt CO₂eq yr⁻¹). Conversely, Europe, Oceania and North America pre- and postproduction processes were led by emissions from food retail (0.3-0.4 Gt CO₂eq yr⁻¹), while South America was dominated by emissions from food waste disposal (0.2 Gt CO₂eq yr⁻¹).

15 3.3 Country Trends

16 Our estimates show a marked variation among countries in terms of total emissions as well as the composition of 17 contributions across farm gate, land use change and pre- and post-processing components (Fig. 5). China had the 18 most emissions (1.9 Gt CO₂eq yr⁻¹), followed by India, Brazil, Indonesia and the USA (1.2-1.3 Gt CO₂eq yr⁻¹). 19 Democratic Republic of Congo (DRC) and Russian Federation followed with 0.5-0.6 Gt CO₂eq yr⁻¹, followed by 20 Pakistan, Canada and Mexico with 0.2-0.3 Gt CO2eq yr⁻¹. The contribution of the three main agri-food systems 21 components to the national total differed among countries significantly (Fig. 5). For instance, China and India had 22 virtually no contribution from land use change to agri-food systems emissions. The land use contribution was also 23 minor in the USA, Russian Federation and Pakistan. Conversely, the latter was the dominant emissions component 24 in Brazil, Indonesia and the DRC. Additionally, the new database allowed for an in-depth analysis by country of 25 pre- and post-production emissions along the agri-food chain, highlighting a significant variety in most relevant 26 sub-process contribution (Tab. 3). For the year 2019, pre- and post-production emissions were dominated in China 27 by food household consumption processes (463 Mt CO2eq yr⁻¹), whereas food waste disposal was the dominant 28 pathway in Brazil, Indonesia (77 Mt CO2eq yr⁻¹), DRC (8 Mt CO2eq yr⁻¹), Pakistan (33 Mt CO2eq yr⁻¹) and Mexico, 29 (56 Mt CO₂eq yr⁻¹). Emissions from food retail dominated the pre- and post-production component in the USA 30 (292 Mt CO2eq yr⁻¹), Russian Federation (177 Mt CO2eq yr⁻¹) and Canada (20 Mt CO2eq yr⁻¹). Finally, on-farm 31 energy use was the largest pre- and post-production component in India (205 Mt CO₂eq yr⁻¹).

32 4 Discussion

The most important 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 postproduction processes along food supply chains, at all scales from global, regional and national, from 1990 to 2019. Our data show that by 2019, food supply chains 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 –having doubled since 1990 to 3.5 Gt CO_{2eq} yr⁻¹. By 2019 food supply





1 chains had become the largest agri-food system component in China (1,100 Mt CO_{2eq} yr⁻¹); USA (700 Mt CO_{2eq}

2 yr⁻¹) and EU-27 (600 Mt CO_{2eq} yr⁻¹). This has important repercussions for food-relevant national mitigation

3 strategies, considering that until recently these have focused mainly on reductions of non-CO₂ gases within the

 $4 \qquad farm \ gate \ and \ on \ CO_2 \ mitigation \ from \ land \ use \ change.$

5 Importantly, the FAOSTAT database presented here allows for an estimation of the percentage share contribution 6 of food systems emissions in total anthropogenic emissions, by country as well as at regional and global levels, 7 over the period 1990-2019. The FAOSTAT-PRIMAP database covering all sectors which underlies this study 8 estimates total anthropogenic emissions at about 52 Gt CO2eq yr⁻¹ without land use, land use change and forestry 9 emissions (LULCUF), and about 54 Gt CO2eq yr⁻¹ with LULUCF-consistently with recent estimates (IPCC, 10 2019). We use the latter figure to compute emissions shares. A number of important issues can be highlighted to 11 this end (Tab. 4 and Fig. 6). First, in terms of CO2eq, the share of world total agri-food systems emissions 12 decreased from 40% in 1990 to 31%. Thus while it is important to note that one-third of all GHG emissions today 13 are generated by agri-food systems, their shares in total emissions may continue decreasing in the near future. This 14 decreasing trend was driven by trends in large regions with ongoing transformations in their agri-food systems and 15 land use change patterns. For instance, in South America, the region with the highest food systems share over the 16 entire study period (Fig. 6), food shares went from 96% to 72% in 2019. In Africa, from 67% to 57%, in Asia from 17 49% to 24% and in Oceania from 57% to 39%. In contrast to these trends however, in regions dominated by modern 18 agri-food systems such as Europe and North America, our data suggest that the overall share of agri-food systems 19 emissions increased from 1990 to 2019, specifically from 24% to 31% in Europe and from 17% to 21% in North 20 America. Such increases in these two regions were due to a disproportionate increase in emission from pre- and 21 post-production activities, as noted earlier, resulting in addition to doubling absolute emission also doubled their 22 underlying shares (Tab. 4). It is also worth noting that in all regions absolute emissions form pre- and post-23 production activities increased from 1990 to 2019, and that such increased in all regions but Africa were 24 accompanied by larger relative shares of this food system component in 2019 compared to 1990.

25 A final analysis on agri-food systems impacts on total GHG emissions would not be complete without a focus on 26 component gases in addition to quantities expressed in CO2eq. The FAOSTAT data confirm the trends form 1990 27 to 2019 seen for total CO2eq emissions, with important features (Tab. 5). First, the impact of agri-food systems on 28 world total CO₂ emissions was 21% in 2019 (down from 31% in 1990), a respectable share considering the 29 importance of carbon dioxide in any effective long-term mitigation strategy. While most regions had contributions 30 around this value, ranging 13%-23% for North America, Oceania, Europe and Asia, the CO2 contribution of agri-31 food systems was higher in Africa (52%) and South America (70%), largely in relation to the land use change 32 emissions that are still significant therein. Additionally, Europe and North America were the only regions where 33 the CO₂ shares actually increased from 1990 to 2019, confirming the growing weight of pre- and post-production 34 processes, which typically involve fossil-fuel energy use. Second, the data highlight the significant contribution of 35 agri-food systems to 2019 world total emissions of CH₄ (53%) and N₂O (78%), also confirmed at regional levels 36 (Tab. 5), linked to farm gate production processes (Tubiello, 2019). Finally, the data highlight a very large increase 37 in agri-food systems contributions of F-gas emissions, which went from near zero in 1990 to more than one-quarter 38 of the world total in 2019 -with larger contributions in many regions. At least with respect to the underlying 39 assumptions made in our methods, such a marked increase was entirely due to strong growth of refrigeration in the 40 food retail sector (Hart et al., 2020; IIR, 2021; Tubiello et al., 2021b).





Another aspect of the dataset underlying this study is that it provides food and agriculture relevant information
 across IPCC and FAO definitions and classifications. In terms of national GHGH inventories, it is worth pointing
 out that while agri-food systems were found to be about one-third of total anthropogenic emissions, our data
 indicated that emissions from land use, land use change and forestry (LULUCF) in 2019 only represented 3-4%,
 while emissions from agriculture, forestry and other land use (AFOLU), were a mere 15% of the total
 anthropogenic emissions.

7 5 Conclusions

8 This paper provided details of a new FAOSTAT domain characterizing GHG emissions along the entire agri-food 9 systems chain, including crop and livestock production processes on the farm, land use change activities from the 10 conversion of natural ecosystems to agricultural land, and processes along food supply chains, from input 11 manufacturing to food processing, transport and retail, including household consumption and waste disposal.

12 The data are provided in open access mode to users worldwide and are available by country over the time period 13 1990-2019. The major trends identified in this work help identify emissions hotspots across agri-food systems and 14 by country, helping to identify areas for effective mitigation actions in food and agriculture. This work adds to 15 knowledge well established in the literature but limited in terms of datasets to farm gate processes and land use 16 change, by adding a wide range of additional details on emissions from pre- and post-production processes. The 17 new data highlight the increasingly important role that these play in the overall emissions footprint of agri-food 18 systems, reflecting a pattern of development from traditional to modern agri-food systems and overall economic 19 growth. The granularity of the dataset allows, for the first time, to highlight specific processes of importance in 20 specific countries or group of countries with similar characteristics. The relevance of the information being 21 provided cuts across several national and international priorities, specifically those aiming at achieving more 22 productive and sustainable food systems, including in relation to climate change. To this end, the work presented 23 herein completes a mapping of IPCC categories, used by countries for reporting to the climate convention, to food 24 and agriculture categories that are more readily understandable by farmers and ministries of agriculture in 25 countries. This helps better identify agri-food systems entry points within existing and future national determined 26 contributions. Finally, the methodological work underlying these efforts complements and extends recent 27 pioneering efforts by FAO and other groups in characterizing technical coefficients to enable quantifying the 28 weight of agri-food systems within countries' emissions profiles. The next steps in such efforts would need the 29 involvement of interested national and international experts in compiling a first set of coefficients for agri-food 30 systems as a pratical 'agri-food systems annex' to the existing guidelines of the Intergovernmental Panel on 31 Climate Change, providing guidance to countries on how to better characterize food and agriculture emissions 32 within their national GHG inventories.

33 6. Disclaimer

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

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1 TABLES

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Process	1990	2019	Change
Net Forest conversion	4,392	3,058	-30%
Enteric Fermentation	2,494	2,823	13%
Livestock Manure	1,101	1,315	19%
Household Consumption	541	1,309	142%
Waste Disposal	984	1,278	30%
On-farm energy use	757	1,021	35%
Retail	128	932	631%
Drained organic soils	736	833	13%
Rice Cultivation	621	674	9%
Fires	558	654	17%
Synthetic Fertilizers	422	601	42%
Transport	327	586	79%
Food Processing	421	510	21%
Fertilizers Manufacturing	152	408	168%
Packaging	166	310	87%
Crop Residues	161	226	40%
Forestland	-3,391	-2,571	-24%

4

5 Table 1. GHG emissions (Mt CO₂eq) by agri-food systems component for all processes considered in this work.

6 Data on forestland removals are provided for completeness of land-based emissions available in FAOSTAT.





1 2

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

3 4 5

5 Table 2. Regional GHG emissions (Gt CO2eq) by agri-food systems component, showing total food systems

6 emissions and percentage contribution of emissions form pre- and post-production processes. 1990 and 2019. The

7 last two columns show the largest sub-component of pre- and post-production emissions by region.





2

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

Table 3. Top ten country GHG emissions (Gt CO2eq) 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.





	Farm gate		Land Use C	hange	Supply C	hains	Food Systems		
-	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%	

5 6 7

Table 4. Regional GHG emissions (Gt CO2eq) by agri-food systems component and total food systems emissions,

8 2019. The last two columns show the dominant sub-component of pre- and post-production processes.





1 2 3

	1990	2019	1990	2019	1990	2019	1990	2019	1990	2019	
	CO ₂ eq		CO ₂		CH₄	CH ₄		N ₂ O		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	
4											

4 5 6

Table 5. World total and regional GHG food systems emissions shares, 2019-2019, for all single GHG and in 7 CO2eq.





1 FIGURE LEGENDS

2

3 Figure 1. Mapping of emissions across agri-food systems. Left-hand panel: IPCC sectors and processes used in 4 national GHG emissions inventories. Right-hand panel: food and agriculture sectors and categories aligned to 5 FAO's definitions.

6

7 Figure 2. World-total GHG emissions from agri-food systems, 1990-2019. Color bars show contributions by 8 emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply 9 chains (blue). Source: FAOSTAT (FAO, 2021). Also shown are emissions per capita (authors' own calculations).

10

11 Figure 3. World total 2019 GHG emission from agri-food systems, showing contributions on agricultural land 12 (left panel) and from pre- and post- production along food supply chains (right panel). Net removals on forest land 13 are also shown, for completeness. The sum of emissions from agricultural land and forest land correspond to the 14 IPCC AFOLU category. Source: FAOSTAT (FAO, 2021).

15

16 Figure 4. Total GHG emission from agri-food systems by FAO regions, 2019. Color bars show contributions by 17 emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply 18 chains (blue). Source: FAOSTAT (FAO, 2021).

19

20 Figure 5. Total GHG emission from agri-food systems by country, top ten emitters, 2019. Color bars show 21 contributions by emissions within the farm gate (yellow); land use change (green) and pre- and post- production 22 along food supply chains (blue). Source: FAOSTAT (FAO, 2021).

23 24 Figure 6. Top panel: Agri-food systems emissions (GtCO2eq yr⁻¹); Bottom panel: shares of agri-food systems in 25 total anthropogenic emissions (%). Data shown by region, 1990-2019. Color bars show contributions component: 26 farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue). Source: 27 FAOSTAT (FAO, 2021).



 $\frac{1}{2}$



IP	occ	Food Systems	C	GHG	i	FAO		
		Activity	CH4	N ₂ O	CO2			
	Ц	Net Forest Conversion	x	x	x	۳ ۳		
	S	Tropical Forest Fires	x	x	x	AN USE IAN		
		Peat Fires	x		x			
	רו	Drained Organic Soils	x		x			
		Burning - Crop residues	x	x			AL LAND	
		Burning - Savanna	x	x				
Ы	ш	Crop Residues		x				
0	a N	Drained Organic Soils		x		FARM GATE	R	
Ľ	E	Enteric Fermentation	x				Ę.	
7	D.	Manure Management	x	x			5	
	AGRIC	Manure Applied to Soils		x			SRIC	<u>A</u>
		Manure Left on Pasture		x			A	TEN
		Rice Cultivation	x					X
		Synthetic Fertilizers		x				
		On-farm Energy Use	x	x	x			ō
		Transport	x	x	x			Ц Ц Ц
	<u>≻</u>	Processing	x	x	x			
	Ř	Packaging	x	x	x			
		Fertilizer manufacturing	x	x	x	ISO	N O	
		Household consumption	x	x	x	D P CTI		
		Retail –Energy Use	x	x	x	A	d	
Ind	ustry	Retail – Refrigeration	x	x	x	ш	õ	
	ш	Solid Food Waste	x			D	đ	
	ST	Incineration			x			
	S	Industrial Wastewater	x	x				
5		Domestic Wastewater	x	x				

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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







4 Figure 2. World-total GHG emissions from agri-food systems, 1990-2019. Color bars show contributions by emissions

5 within the farm gate (yellow); land use change (green) and pre- and post- production along food supply chains (blue).

6 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

5 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).

6







2 Figure 5. Total GHG emission from agri-food systems by country, top ten emitters, 2019. Color bars show contributions

3 by emissions within the farm gate (yellow); land use change (green) and pre- and post- production along food supply

4 chains (blue). Source: FAOSTAT (FAO, 2021).







Figure 6. Top panel: Agri-food systems emissions (GtCO2eq 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).