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Food systems are responsible for a third of global anthropogenic GHG emissions

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We have developed a new global food emissions database (EDGAR-FOOD) estimating greenhouse gas (GHG; CO_2, CH_4, N_2O, fluorinated gases) emissions for the years 1990–2015, building on the Emissions Database of Global Atmospheric Research (EDGAR), complemented with land use/land-use change emissions from the FAOSTAT emissions database. EDGAR-FOOD provides a complete and consistent database in time and space of GHG emissions from the global food system, from production to consumption, including processing, transport and packaging. It responds to the lack of detailed data for many countries by providing sectoral contributions to food-system emissions that are essential for the design of effective mitigation actions. In 2015, food-system emissions amounted to 18 Gt CO_2 equivalent per year globally, representing 34% of total GHG emissions. The largest contribution came from agriculture and land use/land-use change activities (71%), with the remaining were from supply chain activities: retail, transport, consumption, fuel production, waste management, industrial processes and packaging. Temporal trends and regional contributions of GHG emissions from the food system are also discussed.

Food needs to be farmed, harvested or caught, transported, processed, packaged, distributed and cooked, and the residuals disposed of. Each of these steps causes emissions of anthropogenic greenhouse gases (GHGs) and requires energy. Inputs such as fertilizers or energy need to be produced and made available at the right time and location[1–4] with additional associated GHG emissions.

Major datasets of GHG inventories—including those with country coverage (National Inventory Reporting under the United Nations Framework Convention on Climate Change (UNFCCC)), regional or global coverage (for example, the Emissions Database of Global Atmospheric Research (EDGAR, https://edgar.jrc.ec.europa.eu/), GAINS (https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html) and FAOSTAT (http://www.fao.org/faostat/en/#data/))—provide detailed temporal and sectorial evolution of total GHG emissions. Yet, emissions from the food systems are scattered across many different source categories (Supplementary Fig. 1). Global estimates of the share of emissions associated with agriculture, which includes farm gate production and associated land use, have been produced[5], and more recently emission estimates from the various stages of the life cycles of food products have also been made available[6–10]. Another recent estimate of global food-system emissions has been provided by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land[11], attributing between 10.8 and 19.1 Gt CO_2-equivalent (CO_2e) emissions per year to the food system globally, corresponding to 21% to 37% of overall anthropogenic emissions[11,12]. Other studies report good agreement between 'top down' and 'bottom up' methods[13,14] for Europe. The review of available resources for emissions from food systems shows how, overall, available data are based on detailed product-specific life cycle assessment studies[8,14,15] or are using aggregated global data[9,10]. So far, however, studies encompassing global coverage of the whole food-system at country level are missing and, consequently, the total emissions and the total share of those emissions associated with food systems are largely unknown.

The global database of GHG emissions (CO_2, methane (CH_4), N_2O, fluorinated gases (F-gases)) from food systems (EDGAR-FOOD) developed in this Article aims to fill this gap by using a consistent methodological framework. EDGAR-FOOD has been developed to aid the understanding of the activities underlying energy demand and use, as well as agriculture and land-use change, and emissions associated with the production, distribution, consumption and disposal of food through the various stages and sectors of the composite global food system. These data were complemented with data from the FAOSTAT database on GHG emissions from land use related to agriculture[15]. EDGAR-FOOD represents the first database consistently covering each stage of the food chain for all countries with yearly frequency for the period 1990–2015.

Emissions from the food system

A third of global GHG emissions comes from the food system. Our estimate of the contribution of food systems to total anthropogenic GHG emissions was 34% (range 25% to 42%) for the year 2015. Global GHG emissions from the food system were 18 Gt $CO_2e\ yr^{-1}$ (95% confidence interval (CI) 14–22 Gt $CO_2e\ yr^{-1}$) in 2015, with 27% (or 4.9 (95% CI 3.7 to 6.4) Gt $CO_2e\ yr^{-1}$) emitted by industrialized countries (country definitions are regional groupings and are provided in Supplementary Table 2), and the remaining 73% (or 13 (95% CI 10 to 16) Gt $CO_2e\ yr^{-1}$) emitted by developing countries (including China) (Fig. 1). In 2015, 71% of global GHG emissions from the food system was associated with the land-based sector, defined herein as agriculture and associated land use and land-use change activities (the latter will be referred to as LULUC). In industrialized countries, the contribution of the downstream energy-related sectors (53%), which includes industry and waste, was larger than the land-based sector, while in developing countries agriculture and LULUC were the dominant fraction (73%) (Fig. 1).

In 2015, six top emitting economies (the term 'economies' is used to allow the European Union to be considered as a single entity) with individual contributions larger than 6% to the global total GHG

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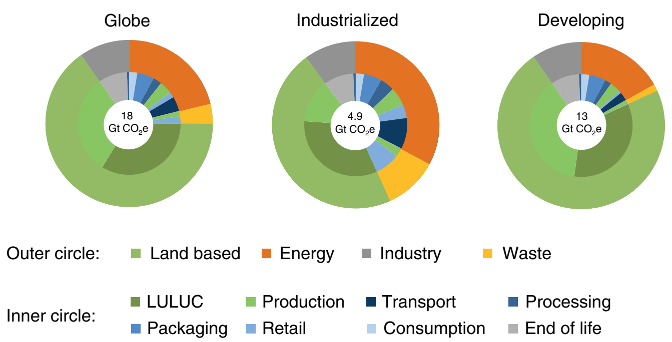

Fig. 1 | GHG emissions from the food system in different sectors in 2015. Total GHG emissions (including CO_2, CH_4, N_2O and F-gases) are expressed as CO_2e calculated using the GWP100 values used in the IPCC AR5, with a value of 28 for CH_4 and 265 for N_2O.

emissions from the food system were responsible for 51% of our estimated global food-system total. They were: China with 2.4 Gt CO_2e (13.5% of the global total), Indonesia with 1.6 Gt CO_2e (8.8%), the United States with 1.5 Gt CO_2e (8.2%), Brazil with 1.3 Gt CO_2e (7.4%), the European Union with 1.2 Gt CO_2e (6.7%) and India with 1.1 Gt CO_2e (6.3%). Supplementary Table 6 reports country-specific contributions to global GHG food-system emissions in 2015.

While food-system GHG emissions increased from 16 (12 to 20) in 1990 to 18 (95% CI 14 to 22) Gt CO_2e yr^{-1} in 2015 (an increase of 12.5%), the share of total GHG emissions decreased over time; that is, it was 10% higher in 1990 (44%) than in 2015 (34%) (Fig. 2a, solid lines). At the same time, global food production, taking cereals as proxy, increased by over 40%, indicating an overall decrease in the emission intensity of food during the same period. The temporal evolution of the share of food-system emissions differed significantly between groups of countries. The share was stable (around 24%) and relatively low for industrialized countries. On the contrary, in developing countries the share of food-system emissions significantly decreased, from 68% in 1990 to 39% in 2015 (Fig. 2a). This food emission trend was nevertheless different when we focused on specific countries: it grew by 41% in China and only by 14% in the rest of the developing countries. The global share of food systems to total emissions slowly decreased to approximately 25%, though a striking decreasing pattern was found for developing countries, where food-system emissions decreased from almost 70% of total emissions to ~40% (Fig. 2a). This sharp decrease, which is in line with previous analyses[16,17], was due to the very high increases in non-food emissions over the period coupled to a significant reduction in land-based emissions, which was largely due to a reduction in deforestation (Fig. 2b).

Emissions from LULUC

Almost one-third of food-system emissions comes from LULUC. According to FAOSTAT, emissions from LULUC associated with agricultural production (IPCC sector 3a) accounted for 5.7 Gt CO_2e yr^{-1} in 2015, or about 32% of total food-system emissions. These emissions are mainly composed of carbon losses from deforestation and from degradation of organic soils, including peatlands[17]. Most of the LULUC emissions (5.0 Gt CO_2e yr^{-1}) occurred in developing countries, thereby substantially affecting the food-system emission share in this country group (Fig. 2a, dashed lines). Furthermore, estimates based on input–output models showed that much of these emissions was associated with food consumption in industrialized countries[18,19].

Energy use in the food system

The global food system is becoming more energy intensive, with almost a third of food-system emissions coming from energy-related activities. While our data confirmed that all life-cycle stages contributed substantially to GHG emissions, the production stages that bring foodstuffs to the 'farm gate' (including fishing, aquaculture and agriculture, plus emissions from the production of inputs such as fertilizers, but excluding LULUC) had the largest share of emissions, contributing 39% (or 7.1 Gt CO_2e yr^{-1}) to total food-system GHG emissions in 2015, followed by LULUC (32% or 5.7 (95% CI 2.8 to 8.5) Gt CO_2e yr^{-1}). Distribution (including transport, packaging and retail), processing, consumption and end-of-life disposal summed to 29% (or 5.2 (95% CI 3.2 to 7) Gt CO_2e yr^{-1}), a share that was higher in 2015 than in 1990 for both the developed and industrialized country groups.

CH_4 emissions accounted for 35% of food-system GHG emissions (expressed in CO_2e) (Fig. 3) consistently across developed and developing countries (32–37%) mainly due to livestock production, farming and waste treatment. (Non-CO_2 GHG emissions (CH_4, N_2O and F-gases) are expressed as CO_2e calculated using the 100 year global warming potential values (GWP100) used in the IPCC Fifth Assessment report (AR5), with a value of 28 for CH_4 and 265 for N_2O.) In most developing countries and globally, rice is one of the leading food crops and a principal source of CH_4 emissions. Asian countries dominate global rice production, and the share of rice production to total food-system emission is 39% in Thailand and 40% in Bangladesh. To put things in perspective, China, India and Indonesia are the top rice-producing countries, followed by Bangladesh, Vietnam and Thailand[20].

While food-system emissions of N_2O were comparable across both groups of countries (9 to 14%), emissions from F-gases (2% of global food-system emissions), mostly linked to refrigeration in the retail stage, were predominantly from industrialized countries (8% of their overall GHG emissions).

Interlinkages between the components of the food-system GHG emissions, including the contribution of different gases to emission sectors and categories and their relation to food supply chain stages, are shown in Fig. 3a, which also shows the respective shares to total food-system emissions and emission trends. Globally, the share of CH_4 slightly increased (an increase of 3% compared with the share in 1990) and total land-based emissions decreased (66% of the total for 2015, which is a decrease of 13% compared with 1990). The share of CO_2 emissions from the energy sector increased (21% of the total in 2015, which is an increase of 31% compared with 1990). This was particularly true for the food processing and distribution stages, which include retail, packaging, transport and processing. All of these stages increased their shares by between 33% and 300% globally compared with the share in 1990. Also, the use of F-gases in industry has increased substantially—by more than 100% since 1990—due to their use in refrigeration. The increased importance of food supply chain emissions was more pronounced in developing countries (Fig. 3c) than in industrialized countries (Fig. 3b), where a particularly steep rise of F-gases for retail (quadrupling the 1990's share) occurred. In developing countries, the share of emissions from agricultural production and LULUC within total food-system emissions dropped significantly (land-based sector shares decreased by 13%, LULUC by 26%), while the share of CO_2 for energy increased by 78%. The share of GHG emissions from waste management, while decreasing in industrialized countries, increased in developing countries (an increase of 50%). Much of the increases in food-system GHG emissions from developing countries occurred in China; without China, emissions from energy were only 10% of total emissions, LULUC increased by 10% and packaging increased by 50%.

Energy use at the farm gate

The overall energy use inside the farm gate, albeit small in its contribution to total food systems emissions, has increased substantially in the past 25 years, but has followed different paths across countries.

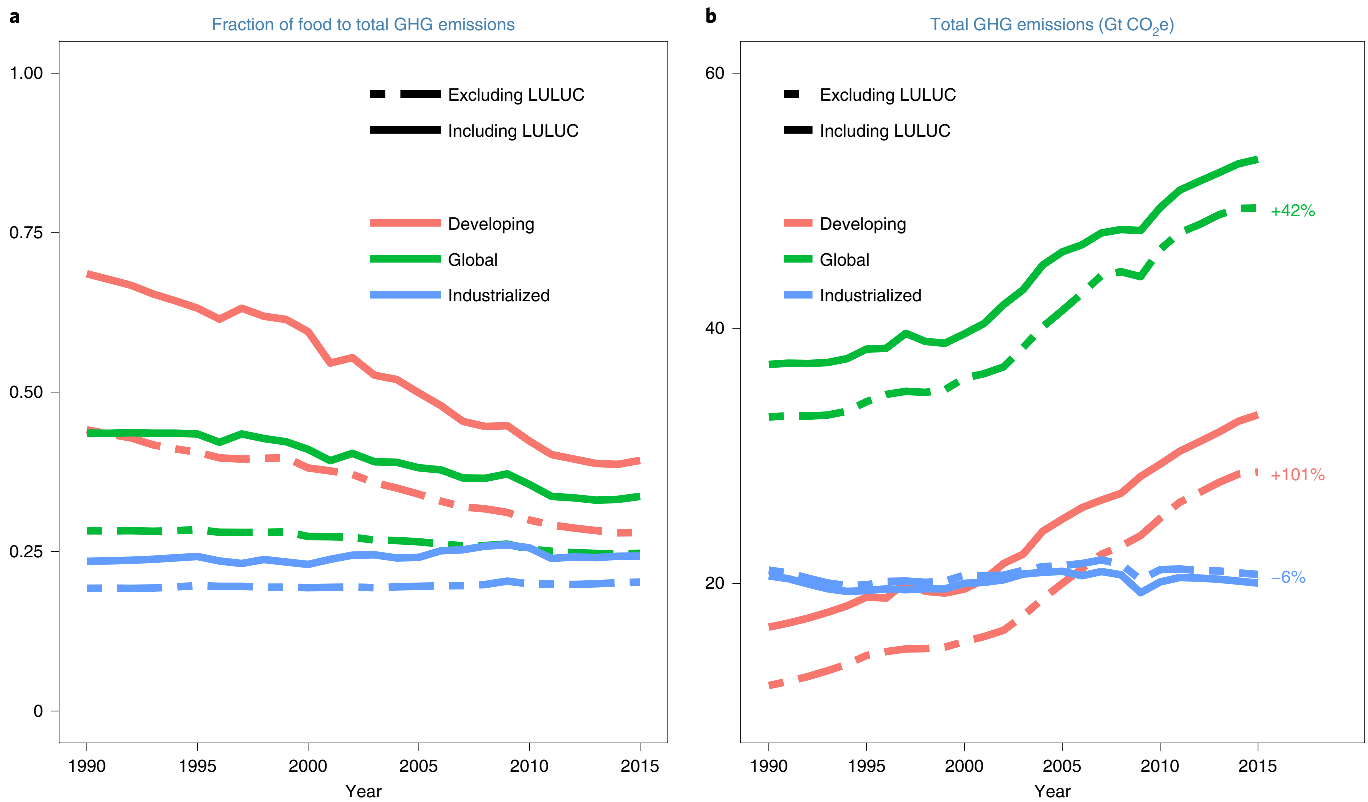

Fig. 2 | Total GHG emissions and food-system data globally, and in developing and industrialized countries. a,b Fraction of food to total GHG emissions (**a**) and total GHG emissions from the food system (**b**) globally, in developing and industrialized countries. Non-CO_2 GHG emissions (CH_4, N_2O and F-gases) are expressed as CO_2 equivalent (CO_2e) calculated using the GWP100 values used in the IPCC AR5, with a value of 28 for CH_4 and 265 for N_2O.

Globally, our data show an increase of 15% in emissions from the use of energy (electricity, heat and fuels) in the agricultural sector compared with 1990, with the highest increase happening in developing regions (an increase of 50%) such as Africa, Latin America and Asia. In these economies, which generally remain strongly agricultural, emissions have increased because agricultural production has become more mechanized, and this includes increased use of fertilizers and pesticides. In addition, agriculture in some developing countries has expanded both to provide food to a steeply growing domestic population and also for export[21]. Conversely, the introduction of agronomic progress and environmental restrictions in agriculture[22] has led to more efficient use of fertilizers and increased efficiencies in livestock production, and nowadays lower emissions from energy used in agriculture (which has decreased 28% compared with 1990) are found in industrialized countries[23–26]. At the same time, emissions associated with use of solvents, which are also used to produce pesticides, increased to 15 times the global level, while solvents used for the production of fertilizers increased by 24%. Significant portions of the increased production were for use in developing countries.

Emissions from food distribution

GHG emissions from food distribution are on the rise but 'food miles' are less important than packaging. Our data show a global food system characterized by an increase in convenience and processed food, and an increasing globalization of the food supply chains everywhere, while at the same time huge differences exist in the distribution and availability of food[27,28]. To function, the food system requires materials and energy for processing, packaging, transporting and storage. Of these, packaging had the highest emissions. In 2015, packaging contributed about 5.4% (or 0.97 Gt CO_2e yr^{-1}) of total food systems emissions (Fig. 4a). Our estimate is higher than previous global estimates[6,29] and might reflect either that our data is more recent or that upstream emissions—including emissions from input and energy production—are included.

However, not all food products and packaging materials are equal. We estimated major contributions from the pulp and paper industry (59.9 (52.7 to 70.7) Mt CO_2e yr^{-1}), aluminium production (29.9 (26.3 to 35.2) Mt CO_2e yr^{-1}), the metal industry (10.6 (9.3 to12.5) Mt CO_2e yr^{-1}) and use of glass (4.8 (2.2 to 7.7) Mt CO_2e yr^{-1}). This is consistent with the findings reported by Poore and Nemecek[6], who show a significant share of packaging-related emissions for beverages (wine and beer, > 40%) and some fruit and vegetables (10–22%).

In view of the public and academic debate on 'food miles'[30–32], we estimate that transportation contributes 4.8% (or 0.86 (95% CI 0.30 to 1.5) Gt CO_2e yr^{-1}) to food-system GHG emissions, approximately the same as retail (4.0% or 0.72 (95% CI 0.21 to 1.44 Gt CO_2e yr^{-1})). Our estimates indicate that due to the huge variations in energy needed per transported 'food mile' (from marine shipping at 10–20 MJ t^{-1} km^{-1}, road transport at 70–80 MJ t^{-1} km^{-1} and aviation at 100–200 MJ t^{-1} km^{-1} (ref. [8])), the majority of emissions arise from local to regional transport via road (81%) or rail (15%), rather than navigation (3.6%) or aviation (0.4%). Urban policy and food logistic policies could thus play a significant role in improving the energy efficiency of food systems[33]. Transport-related GHG emissions are higher for heavy or easily perishable products, and some food products have a particularly high share of transport GHG emissions (>40% for bananas and beet sugar, according to Poore and Nemecek[6]). However, for road transport, detailed data were available only for Europe and the United States, and an average value based on these data was used for all other countries, and therefore

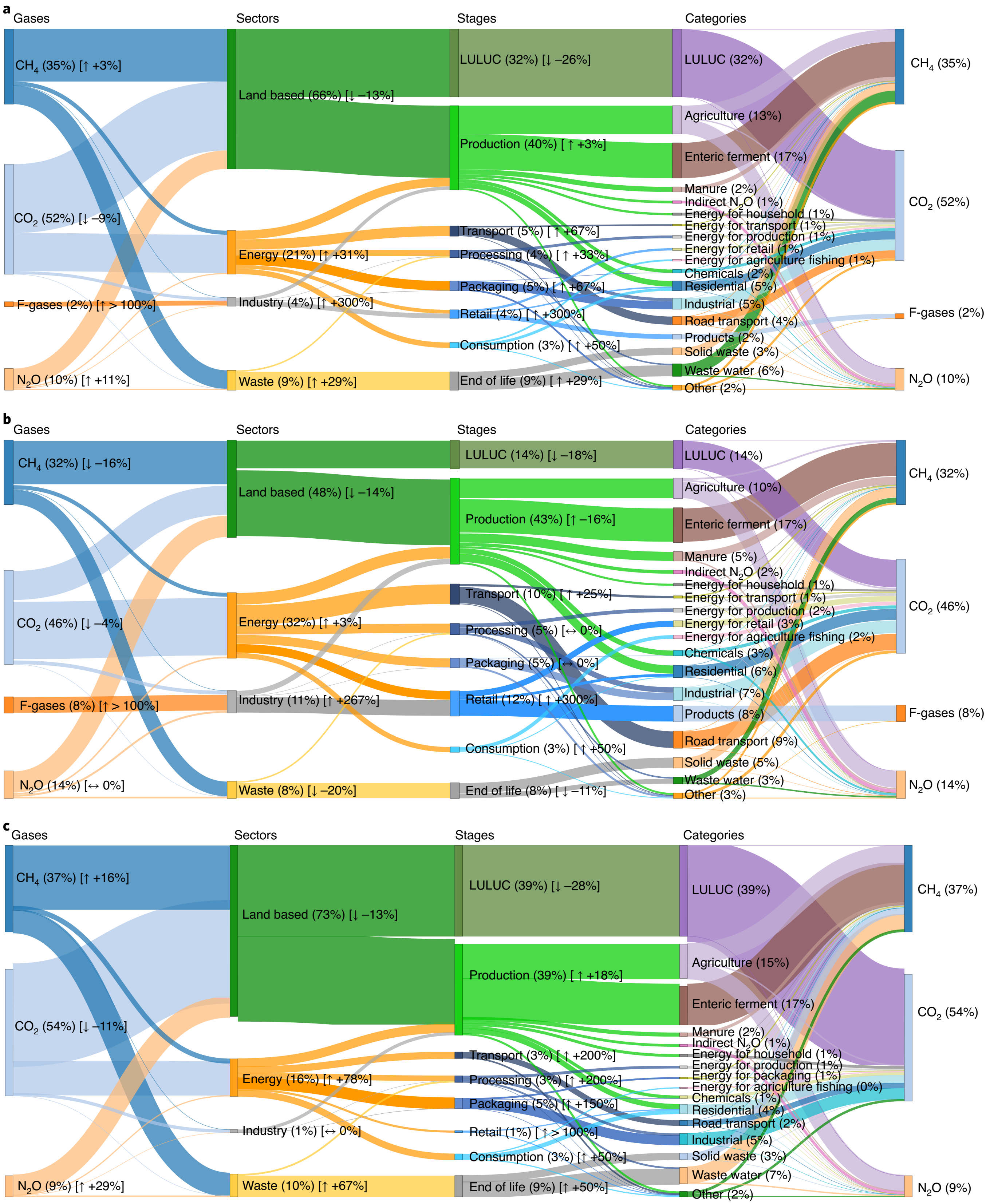

Fig. 3 | Sankey diagram for GHG emissions from the food system in 2015. a, Global. **b**, Industrialized. **c**, Developing countries (including China). Total GHG emissions of the food system were 18 Gt CO_2e yr^{-1} in 2015. The qualitative information of the activities contributing to the food system provided by the Sankey diagram is complemented with the quantitative contribution of individual GHG and sector shares to the total GHG food-system emissions. Arrows and percentages indicate the change in gas, sector, stage and category contributions between 1990 and 2015. Numbers are rounded and therefore do not necessary sum up to 100%.

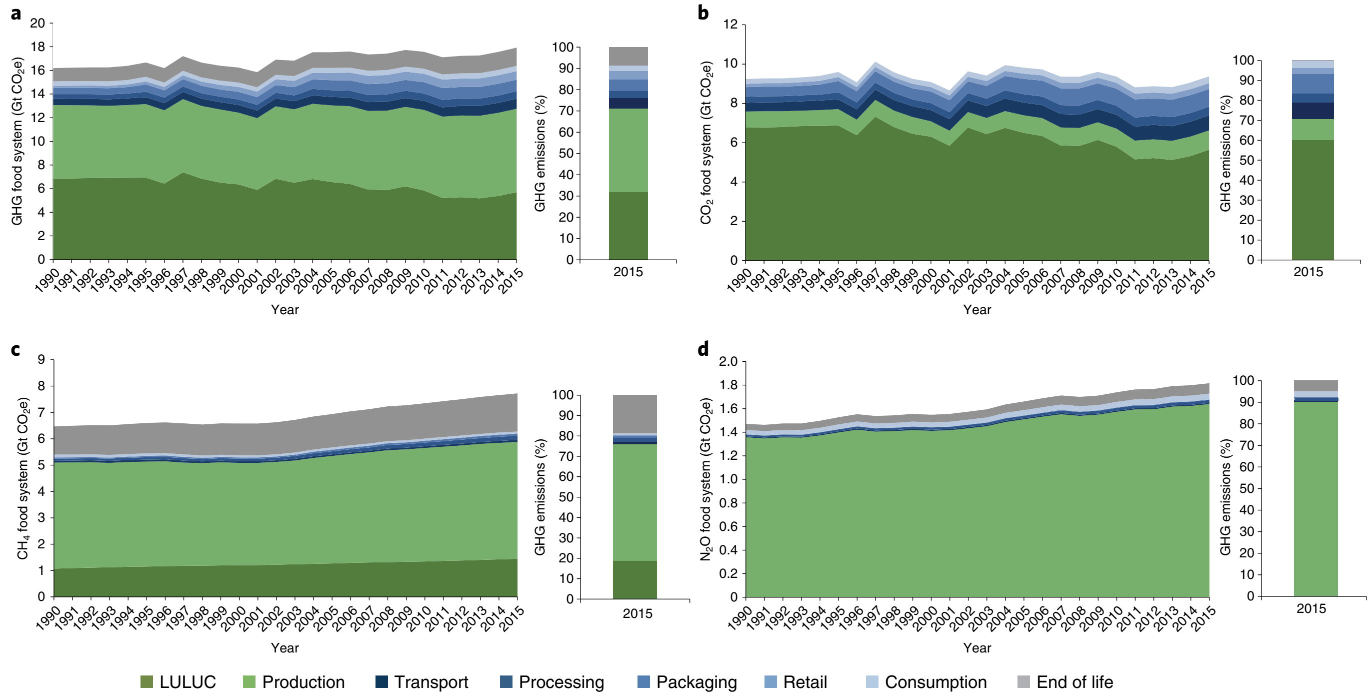

Fig. 4 | GHG emissions trends of the food system by sector. a, Total GHG emissions in CO_2e. **b–d**, Emissions of individual GHGs are represented (CO_2 in **b**, CH_4 in **c** and N_2O in **d**). Non-CO_2 GHG emissions (CH_4, N_2O and F-gases) are expressed as CO_2e calculated using the GWP100 used in the IPCC AR5, with a value of 28 for CH_4 and 265 for N_2O.

these data are associated with large uncertainties. For shipping, aviation and railways, global average values, which may not adequately reflect the situation for individual countries, were used.

Globally, refrigeration has been estimated to be responsible for 43% of energy consumption by the retail/supermarket sector[34]. Our data suggest that GHG emissions from the retail sector increased by 4.2 and 3.6 times in Europe and the United States, respectively, between 1990 and 2015. An increase in the market share of supermarkets in the food distribution sector has been observed in all continents, including Africa, Asia and South America[35–37]. Supermarket refrigeration is not only energy intensive, but also generates leakage emissions of substitutes for ozone-depleting substances, although their contribution to food-system GHG emissions is estimated to be minor. This 'cold chain', including both industrial and domestic refrigeration, accounts for 5% of global GHG food-system emissions, but given that the number of refrigerators per capita in developing countries is about one order of magnitude lower than the number in developed countries, the importance of refrigeration to total GHG emissions is likely to increase[38].

Share of food-system GHG emissions

The share of food systems as a percentage of total anthropogenic GHG emissions varied significantly across countries and regions (Fig. 5), and varied between 14% and 92%. A high share of food-system GHG emissions can be a sign of a strong agri-food sector or of a weak economy. Large shares of food-related emissions found for selected countries in 2015 can be the consequence of different factors: (1) low-income countries where local industry and other economic sectors other than agriculture are relatively small (mostly in Africa and south-eastern Asia), (2) an important food exporting industry such as in Brazil, Argentina and other South American countries, or (3) high food-system emissions from LULUC, as found in Brazil, Indonesia and African countries. For example, in west Africa, to satisfy nutrition needs associated with a fast-growing population, the trend for the share of food-system emissions showed an increase from 69 to 79% (from 1990 to 2015, respectively). Conversely, in China the share fell from 51% in 1990 to 19% in 2015 due to the industrialization of the country and large trade flows of agricultural commodities[39], which reflected a shift between land-based and energy-associated GHG emissions in the food system. Our results are consistent with the rapid transformation of food systems in developing regions[40]. Overall, the most energy intensive economies (for example the United States, Canada, Europe, China and Japan) showed the lowest contributions of food-system emissions to total GHG emissions.

In Brazil, GHG emissions from the food production sector decreased by about 30% from 1990 to 2015, primarily due to substantial decreases in deforestation rates. This decrease occurred despite continuous increases in emissions due to livestock production activities and an increase in the exports of beef and soybean by 720% and 530%, respectively[41].

In sub-Saharan African countries, food production is still to a large degree realized by smallholder farms[42], and eastern and western Africa show shares of land-based food-system GHG emissions of 88% and 69% in 2015, respectively (Fig. 5). Ricciardi et al.[43] estimated that, globally, farms smaller than 2 ha produce 30–34% of the food supply on 24% of the gross agricultural area. To feed a population that doubled in size between 1990 to 2015, Nigeria increased rice production resulting in four times higher GHG emissions from this sector[44], and in 2015 Nigeria emitted more than a third of food-system GHG emissions of the whole western African region. Livestock production emissions increased by 2.8 times compared with 1990 mainly due to the introduction of goats in addition to cattle. As a result of population growth, domestic waste water emissions increased by 3.4 times as well. In Ethiopia, the population doubled between 1990 and 2015, making the country the largest emitter of GHGs from the food system in eastern Africa. The Ethiopian food system contributes to 78% of anthropogenic GHG emissions, with high emissions from cattle which increased by 2.5 times over the same period[45].

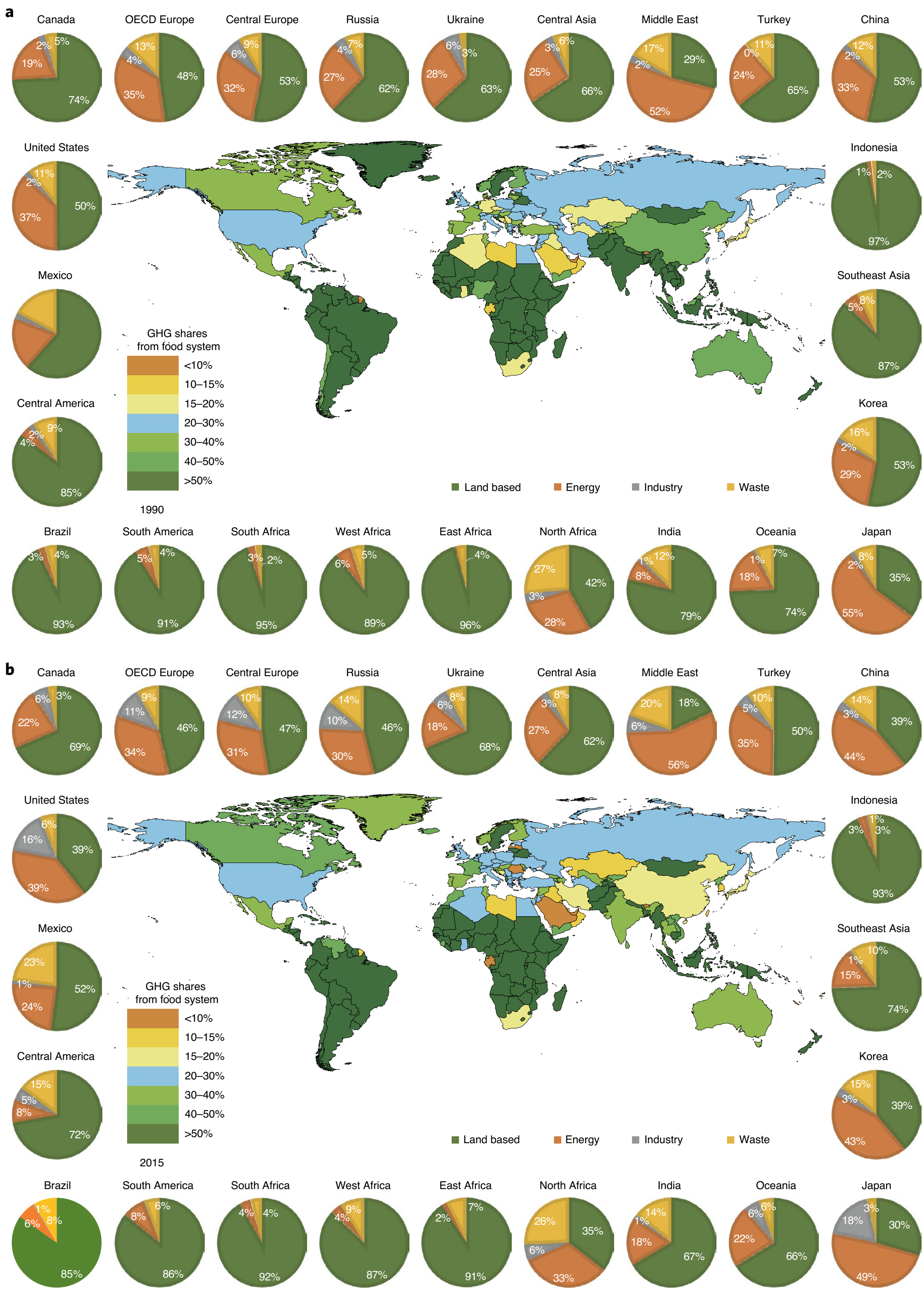

Fig. 5 | GHG emissions from the food system. a,**b**, Pie charts show the contribution of the different food-system sectors (land-based, energy, industry and waste) to GHG emissions from food in 1990 (**a**) and 2015 (**b**). The colours on the map show the share of GHG emissions from food systems as a fraction of total GHG emissions (detailed GHG food-system shares by country are reported in Supplementary Table 4). Total GHG emissions (including CO_2, CH_4, N_2O and F-gases) are expressed as CO_2 equivalent (CO_2e) calculated using the GWP100 values used in the IPCC AR5, with a value of 28 for CH_4 and 265 for N_2O. OECD, Organisation for Economic Co-operation and Development.

Table 1 | Share of GHG emissions from the food system versus total GHGs (including LULUC) for world regions

	Total GHG emissions (from food systems), Gt CO_2e, 1990	Total GHG emissions (from food systems), Gt CO_2e, 2015	GHG shares from food system (%), 1990	GHG shares from food system (%), 2015	Share to global emissions (%), 1990	Share to global emissions (%), 2015	Per capita GHG emissions from food system (t CO_2e cap^{-1} yr^{-1}), 1990	Per capita GHG emissions from food system (t CO_2e cap^{-1} yr^{-1}), 2015
World	36.5 (16.1)	52 (18)	43	34	100	100	3.0	2.4
By continent								
Africa	3.8 (2.7)	4.7 (3.1)	69	67	16	17	4.6	2.8
Asia	9.8 (5.7)	24.0 (7.1)	58	29	35	39	1.9	1.8
Europe	5.6 (1.4)	4.2 (1.3)	26	30	8.8	7.1	2.8	2.4
Latin America[a]	3.8 (3.2)	4.5 (3.0)	84	66	20	17	7.1	4.7
North America	6.5 (1.5)	7.3 (1.9)	23	25	9.1	10	5.3	5.2
Oceania	0.5 (0.2)	0.7 (0.3)	47	38	1.5	1.4	11	8.2
Russia[b]	6.5 (1.4)	6.6 (1.3)	22	20	8.9	7.4	3.1	2.2

The share of each region to global GHG food emissions is reported in brackets. Supplementary Tables 3 and 4 report country-specific food-system emissions and their share as a percentage of total GHG emissions. Total GHG emissions (including CO_2, CH_4, N_2O and F-gases) are expressed as CO_2e calculated using the GWP100 values used in the IPCC AR5, with a value of 28 for CH_4 and 265 for N_2O. [a]Including Central and South America. [b]Including Russia, Ukraine, Central Asia, the Middle East and Turkey.

Per capita emissions from the food system

Our data support the estimation of global food-system GHG emissions with broad coverage of emission sources, as well as with regional and temporal detail. On average, each person's food-related emissions in 2015 were 2.4 (2.1–2.9) t CO_2e. This represented a decrease relative to 1990 levels, when per capita food-related emissions were 3.0 (2.3–3.8) t CO_2e. Table 1 reports the evolution of food-system emissions as a percentage of the national total GHGs and global food-system emissions from 1990 to 2015 by continent and region. Table 1 also shows the development of per capita food-system GHG emissions. These numbers are not to be mistaken for consumer GHG footprints, which are determined by the actual diet in a specific country and assign emissions occurring throughout the food supply chain to that country. Our data reflect the structure of the countries' food system and economy. They are consistent with how GHG inventories are reported to the UNFCCC and can be used to benchmark national mitigation efforts to reduce GHG emissions from food systems. Effective policies to transform food systems towards sustainability need to be comprehensive and provide answers and adequate information[46] to both the economy and its consumers. Policies also should address both food production and food consumption[47–50].

Conclusions

EDGAR-FOOD provides a picture of how an evolving world food system has responded to the evolution of world population in the last 25 years, which has coincided with changes in dietary habits and food-related technology. At the global level, the decoupling of population growth and food-related emissions is visible with emissions growing at a lower rate compared with population growth. The regional view is more diverse, with some areas rapidly increasing emissions due to domestic demand for either food or export.

Unlike overall GHG emissions, the food production sector is not overwhelmingly dominated by CO_2 emissions from fossil fuels; land-based emissions are particularly relevant. Nevertheless, in line with the ongoing socio-economic development trends, food emissions are being increasingly determined by energy use, industrial activities and waste management. On the one hand, from the point of view of mitigation, such a trend suggests that the food sector will need specific sectorial energy efficiency and decarbonization policies. (For instance, the food industry generally requires lower heating temperatures than other types of industrial production, and those lower temperatures are more easily reached by non-fossil-based technologies.) On the other hand, the continuing predominant role of land-based emissions, within and outside the farm gate, shows that food production itself will continue to be a major source of emissions that will require dedicated mitigation policies.

The global food emissions database EDGAR-FOOD provides a broad level of geographical, temporal and thematic detail of national GHG emissions from the global food system and represents a milestone in our understanding of how the global food system has developed. With its detailed and consistent dataset of the emissions related to the various stages of the food system, it is possible to estimate the changes in food-system GHG emissions driven, for example, by consumer behavioural changes or technological evolution. Moreover, it is crucial to the anticipation of future changes in the overall food system and to the design of efficient mitigation strategies that avoid creating additional emissions in non-targeted sectors. Owing to its completeness and flexibility, our dataset is intended as a tool for the scientific community to allow researchers to focus on specific sectors or groups of sectors, freely aggregating and splitting data to design their investigations.

The completeness of the EDGAR-FOOD database is an important asset for effectively monitoring global food-system GHG emissions. This database is in line with the strategies that work with an integrated view of the food system, such as the new European Commission's Farm to Fork Strategy[46].

Methods

We developed the new food emissions database (EDGAR-FOOD) using the EDGAR[51] covering the IPCC sectors 'Energy', 'Industry', 'Agriculture' and 'Waste' (see Supplementary Fig. 1). We complemented the EDGAR-FOOD data with the FAOSTAT database[52] for emissions and sinks in the LULUC sector. EDGAR-FOOD provides detailed, highly disaggregated and harmonized emission estimates covering all sectors and geographical areas using a rigorous and transparent process of data integration and verification. The EDGAR and FAOSTAT data are widely used for climate research and as a basis for global climate policies, and they are also used in the IPCC Fifth and Sixth Assessment Reports.

For EDGAR-FOOD, we complemented the EDGAR database with estimates of the food-system emission shares for each of the source categories. One of the challenges of compiling EDGAR-FOOD is to calculate the food-related portion of industrial and energy processes that impinge on other sectors (for example, the glass industry, energy production and waste, among others) for each country, while preserving global consistency. Details on the share of food-system emissions for each source category (value, method and uncertainty level) are given in Supplementary Table 1. Assumptions made and uncertainties are discussed below. Supplementary Table 1 also indicates the life-cycle stage and the food-system sector to which the source categories are assigned.

We distinguish six life-cycle stages in food systems: (1) LULUC: land use, land-use change; (2) production: primary production of food commodities; (3) processing: food processing; (4) distribution: food distribution including packaging, transport and retail; (5) consumption: food consumption including domestic activities of food preparation; and (6) end of life: end of life of food, including food residues management and management of non-food residues used in previous food-system stages.

EDGAR-FOOD allocates the extraction of raw materials and the production of inputs required for primary food production, and the provision of primary energy is assigned to each individual stage.

We distinguish the following food-system sectors: land-based sector (including crop and livestock products and LULUC), energy, industry and waste.

Food-system emissions calculation at the global scale. The quantification of food-system GHG emissions is done using the EDGARv5.0[51] (https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG) as the underlying source of global GHG and air pollutants at country scale. Emissions are calculated using a bottom-up methodology complying with IPCC guidelines[53], with high sectorial disaggregation[54,55] (https://edgar.jrc.ec.europa.eu/index.php). GHG emissions are computed in EDGARv5.0 mostly following the IPCC Tier 1 approach, while a Tier 2 method is applied to estimate emissions from cattle enteric fermentation, rice cultivation, waste treatment and cement production. The 2019 IPCC refinement guidelines are not included in EDGARv5.0, and therefore they are not part of this work.

The EDGAR inventory has been coupled with shares describing the contribution of the food system to each emissions sector (Supplementary Table 1). Food-system GHG emissions are calculated by multiplying these sectorial food-system shares (SFSs) with the total emissions of each sector (equation (1)). Specifically, SFS equals 1 if the whole sector is part of the food system, such as food and beverage sector, while SFSs for sectors only partly representing the food system (for example, transportation) take a value from 0 to less than 1:

$$E_{i,c,t}^{Food} = \sum_{s=1}^{n} E_{i,s,c,t} \times \mathrm{SFS}_{s,c,t} \tag{1}$$

where i represents each greenhouse gas (fossil CO_2, CH_4, N_2O and F-gases), c is each world country, t is each individual year (from 1990 to 2015), s are all emitting sectors in EDGAR, E is the emission of a certain sector, and SFS is the sectorial food-system share. SFS is defined per sector or subsector and can vary between countries and years, depending on the availability of data. In those cases when detailed information was not available, a global average share was adopted, though this does not reflect country-to-country variations, but still represents the best available knowledge to complete the global picture. Dependency of the shares on time, country and fuel type is indicated in Supplementary Table 1.

Attribution of primary energy emissions to the food system. Energy consumption in the food system causes GHG emissions at different stages: (1) emissions caused by combustion in large and small scale industries, households, transport or other food-system actors; (2) emissions caused by centralized heat and electricity production that is consumed by food-system actors; (3) emissions caused by the 'fuel chain', including fuel extraction, transport and leakage; and (4) indirect GHG emissions caused by any of the above sources.

Emissions from 1–4 are available by fuel-type and sector.We developed an estimate for SFS for each sector with emission estimates available in EDGAR. We then calculated food-system emissions from centralized heat and electricity production, fuel chain emissions and indirect GHG emissions from energy consumption according to points 2 and 3.

Fuel combustion. Within the food-related power generation emission sectors, we considered the food production industry, fishing and food-related agriculture, packaging production, household and retail/services activities as those consuming electricity and heat for food-related purposes. We assumed that the total heat and electricity from fishing, food-related agriculture and food production contribute to food-system emissions. Shares reflecting the use of energy in the food system (for example cooking, refrigeration and so on) are calculated and applied to the packaging industry (for example, share of packaging used for food), household (for example, cooking, refrigeration and so on) and retail/services sectors (for example, food retail and grocery, restaurants and so on), as discussed below.

Heat and electricity production. Shares of energy used in the food system are based on International Energy Agency (IEA) electricity and heat consumption data[56], detailed by country and subsector. The electricity shares by subsector are then applied to the EDGAR-FOOD emissions from power generation, in particular from public electricity and cogeneration plants as well as from auto producers of electricity and cogeneration. The shares of heat are applied to the emissions from auto produced heat plants and district heating plants. $\mathrm{SFS}_{s,c,t}$ varies (minimum–maximum) between 4.4×10^{-5} and 0.13 depending on the year, country and subsector.

Fuel chain. Emissions from the fuel production sector have been calculated by allocating the emissions from fuel production, transformation and refineries, and determining the shares of each fuel that are used in the food system. This share is calculated as CO_2 emissions from combustion of a specific fuel for each food-system category over the total CO_2 emissions from combustion of the fuel in the country on an annual basis. These emissions represent the contribution of the fuel chain to the food system and allow quantification of the emission reduction through the full chain when reducing certain activities. $\mathrm{SFS}_{s,c,t}$ varies (minimum–maximum) between 0.0003 and 0.87 depending on the year, country and fuel.

Indirect emissions. Indirect N_2O emissions from ammonia (NH_3) and nitrogen oxide gases (NO_x) emitted by IPCC categories 1A ('energy'), 2 ('industrial processes and product use') and 3 ('agriculture, forestry and other land use') related to the food system only are included. Indirect N_2O emissions from leaching and runoff of nitrate are estimated from nitrogen input to agricultural soils. Indirect N_2O emissions from atmospheric deposition of NO_x and NH_3 emissions from agricultural (crop residues, synthetic fertilizer, animals in pasture and manure input to soils) and non-agricultural sources (mainly fuel combustion and industrial processes) are estimated using nitrogen in NO_x and NH_3 from these sources as activity data. More details can be found in Janssens-Maenhout et al.[55].

Details of food-system emissions by life-cycle stage. *LULUC.* Agricultural land-use emissions involved in food production are those associated with carbon losses due to relevant LULUC. These include emissions from deforestation and from the degradation of organic soils (drainage and fires), which are derived by applying the relevant IPCC guidelines[53] and are available in the FAOSTAT Emissions-Land Use domain[52]. They exclude forest removals in remaining forest land, as these are not typically related to crop and livestock production. While these associations to food systems are those employed in recent literature (for example, Tubiello et al.[18], IPCC Special Report on Climate Change and Land[11,52] and Rosenzweig et al.[12]), the main limitations to this approach arise from the assumption, in the absence of more detailed information, that all deforestation is associated with a conversion to agricultural land. However, we know that, globally, about 80% of deforestation is associated with agricultural expansion (IPCC, AR5 WGIII Ch 11)[57]. Furthermore, it should be noted that the FAOSTAT deforestation estimates are based on information about forest land area and carbon biomass, which countries report to FAO every ten years (on average) via the Forest Resources Assessment (FRA). For this reason, annual deforestation estimates are averages for the periods 1990–1999, 2000–2009 and 2010–2015, and may exhibit discontinuities across successive FRA reporting periods. We have not attempted to smooth out such changes because similar jumps can be observed in country reporting to the UNFCCC[58].

Land-use emissions associated with the drainage and burning of organic soils, including peatlands[59–61], are also included. While these data are well validated for Southeast Asia, there is significant uncertainty in national data outside of this region[62,63]. This is especially true in tropical central African countries, despite the fact that the agricultural expansion on organic soils is well documented in tropical peatlands around the world. Furthermore, non-CO_2 emissions from the burning of biomass in humid tropical forests are included as an additional contribution to deforestation emissions[63]. Burning of biomass in tropical rainforests and tropical moist forests, as well as emissions from peat fires[64], are assumed to be associated with deforestation events for agricultural purposes.

Finally, we are not considering in our estimates carbon removals on agricultural land that may arise from important, specific soil management techniques, for instance, reduced tillage or no tillage. While these actions have important mitigation consequences in relation to food systems (see IPCC Special Report on Climate Change and Land[11]), neither FAOSTAT nor any other available global dataset currently provides this information at the level needed for this assessment. Considering that the majority of emissions included in this study are from large-scale deforestation in some developing countries, and that most of the existing soil carbon sequestration techniques are currently in place in a small portion of the total cropland area of some developed and emerging economies, we estimate that the impact of including such soil carbon sequestration data—if it existed—would nonetheless be small compared with the results discussed herein.

Uncertainty in land-use emissions data is typically high. Uncertainty of the FAOSTAT emissions estimates was estimated at about 50% for deforestation data[58] and over 100% for peatland degradation data[65].

Production. Agriculture. Agricultural emissions contributing to the food system include cultivation of food and non-food crops and livestock production. Here we considered the following emissions from agricultural soils to entirely contribute to the food system (SFS = 1): animal waste as fertilizer, animals in pasture, cultivation of food crops, drainage of organic soils for crop cultivation, CO_2 from urea fertilization, limestone and dolomite use, nitrogen-fixing crops, agricultural waste burning, manure management and enteric fermentation[51]. We quantified the use of fertilizers for non-food crops based on the FAO report[66] on the use of fertilizers for different world regions as well as the US Department of Agriculture (USDA) data for the United States (https://www.ers.usda.gov/data-products/fertilizer-use-and-price/). We validated the reported values on the basis of our own calculations of GHG emissions using FAOSTAT commodity balances (http://www.fao.org/faostat/en/#data/BC) and nitrogen content data from Lassaletta et al.[67] and Leip et al.[68]. Fibres are by far the most important non-food crops, with the export of nitrogen in cottonseed more than three times as important as tobacco, the second relevant non-food crop. Therefore, we focused our analysis on fibre crops. FAO quantified that, globally, 4.4% of fertilizers are used for fibre cultivation[66]. They provided more detailed regional values, reporting the highest use of fertilizers for fibre cultivation in India, Pakistan, Bangladesh and Sri Lanka. In the European Union, the use of fertilizers for non-food–related crops is also rather negligible[69]. For the United States, we apply a share of non-food use of fertilizers of 3%, based on USDA statistics (https://www.ers.usda.gov/data-products/fertilizer-use-and-price/). Overall, $SFS_{s,c}$ varies (minimum–maximum) between 0.922 and 1 depending on the country and region.

Indirect N_2O emissions from NH_3 and NO_x emitted by all agricultural activities are also included. Emissions from combustion in food-related agricultural and fishing activities[56] are entirely included in the food-system GHG emission calculations, while no emissions are allocated to non-food co-products such as straw, fish-oil drugs or pet food.

Chemicals. Emissions from chemical production are available for chemicals related to plastic production (acrylonitrile, ethane/ethylene, methanol, vinyl chloride, adipic acid, caprolactam, glyoxal, calcium carbide) and to fertilizers[70–72] (ammonia, SFS = 0.8; urea, SFS = 0.9; nitric acid, SFS = 0.7). For chemicals used for plastics, the same shares of plastic packaging described in the following are used.

Solvents. Emissions from solvent production and use in pesticides and vegetative oil extraction are entirely attributed to food production (SFS = 1). No other solvents are relevant to the food-system emissions.

Processing. The contribution from combustion in the food and tobacco industry (including beverages) is entirely accounted to food-system emissions (SFS = 1), and it is based on IEA data[56].

Distribution. The distribution stage includes emissions from food packaging, transport and retail.

Packaging. We estimate emissions from food packaging for iron and steel, paper, aluminium, plastic, and glass containers and bottles.

- Iron and steel
  Emissions from iron and steel production are associated with the production of tin and are calculated using country-specific statistics on the amount of iron and steel used for tin mill products, available from the World Steel Association[73,74,75] for the whole time series. An average global share of tin mill products used for food packaging is available from the World Steel Association[54] ($SFS_{s,c,t}$ minimum–maximum range: 0.0014–0.079).
- Glass
  The fraction of glass used for food packaging is estimated based on European[76] (with country-specific information) and global[77] statistics ($SFS_{s,c,t}$ minimum–maximum range: 0.45–0.62). In addition, emissions from the use of soda-ash for glass production for food containers and bottles[78] are included ($SFS_{s,c}$ minimum–maximum range: 0.225–0.31).
- Plastic
  To calculate how much plastic is used for food packaging, we first evaluated how much plastic is refined and transformed from oil and gas fuels produced as a global average[56,79]. Then the fraction of plastic used for packaging for world countries or regions was taken from UNEP[80]. In the lack of more specific data, we applied a global average fraction of plastic packaging used in the food system[81] (SFS_s minimum–maximum range: 0.000018–0.00132).
- Paper
  FAOSTAT[82] reports data on total paper production and paper production for writing purposes. We assume that the remaining fraction is used for packaging. A global average share of paper used for food is applied only to 'kraft paper' and 'other paper and paperboard' components which are present in the EDGAR database and not strictly used for writing purposes ($SFS_{s,c,t}$ minimum–maximum range: 0.089–0.439).
- Aluminium
  The Global Aluminium Flow model[83] provides an historic time series (1971–2018) of aluminium production used for packaging (cans and foil) for some countries/regions (the United States, Canada, Europe, Russia, China, Japan, South Africa, Brazil, India and Australia) as well as for the rest of the world. We assume that the aluminium was entirely dedicated to food packaging ($SFS_{s,c,t}$ min-max range: 0.059–0.338). The same shares are also used to estimate food packaging GHG emissions from SF_6 use in aluminium foundries.
  Emissions from combustion in manufacturing industries related with the food system are computed based on IEA data[56]. An $SFS_{s,c,t}$ value that is less than unity, corresponding to the share of the food packaging production as a fraction of the total production, is assumed for industries that produce paper ($SFS_{s,c,t}$ minimum–maximum range: 0.089–0.439), plastic (SFS_s minimum–maximum range: 0.000018–0.00132), non-metallic minerals (glass production, $SFS_{s,c,t}$ minimum–maximum range: 0.225–0.62) and non-ferrous metals (aluminium, $SFS_{s,c,t}$ minimum–maximum range: 0.059–0.338; iron and steel, $SFS_{s,c,t}$ minimum–maximum range: 0.0014–0.079) since these industrial processes are also important emitters of GHGs. The shares associated with the food packaging industries are applied both to the emissions from processes and combustion.

Transportation. EDGAR includes detailed emissions from international shipping based on the work of Dalsøren et al.[84]. Emissions from reefers (in port and at sea) and fishing vessels (in port) have an SFS = 1. For general cargo vessels (carrying packaged items like chemicals, foods, furniture, machinery, motor and military vehicles, footwear, garments and so on) and for dry bulk carriers (carrying coal, grain, ore and other similar products in loose form), shares representing the contribution to the food system[85] are applied (SFS minimum–maximum range: 0.022–0.029).

A fraction of road transport emissions associated with heavy duty, light duty and passenger cars is attributed to the food system based on data for Europe from Eurostat[86] and from FAO[87] for the rest of the world (SFS minimum–maximum range: 0.11–0.15).

A world average share of emissions related to the food system from international and domestic aviation (SFS = 0.005) as well as from inland waterways (SFS = 0.07) and railways (SFS = 0.155) is estimated from FAO data[8].

Retail. The share of electricity used in retail activities (for example, refrigeration, a quota of space heating, air conditioning and lighting for food-related activities) in Europe in the household sector as a fraction of the total consumption in that sector is computed using Eurostat data as summarized by Thomas[88].

The electricity used for cooking and refrigeration for different types of retail activities (food sales and food services, retail (other than mall), enclosed and strip malls, warehouse and storage) is retrieved for the United States from EIA data[89]. For the rest of the world, the electricity consumption for cooking is calculated for China, India and Africa and as a world average based on region specific data[90,91]. These shares are applied to the electricity used in the retail sector and then applied to the energy emissions.

We also evaluated the amount of different fuels (for example gas, oil, solid) burnt in the retail sector for food-related activities (for example cooking, space and water heating) and calculated the corresponding share to be applied to retail combustion emissions. Eurostat[88] and EIA[89] data were used for Europe and the United States. For the rest of the world countries, the shares of the food system associated with retail are assumed to be the same as for the household sector based on the Eastern Research Group report[91]. Overall, $SFS_{s,c,t}$ for the retail sector varies (minimum–maximum) between 0.003 and 0.265.

In accord with the IPCC guidelines[92], the main F-gases used for refrigeration are HFC-134a (in EDGAR we already have the fraction used for refrigeration), HFC-32, HFC-143 (entirely used for refrigeration, although a smaller share could be attributed to non-food refrigeration such as of pharmaceutical products) and HFC-125 (which is mainly used for refrigeration and partly for fire protection). Therefore, the SFS for this sector is 1.

Consumption. The share of electricity used for food-related activities (for example, cooking, food refrigeration, microwave ovens, coffee makers, toaster and so on) in Europe in the household sector over the total consumption in that sector is computed using the corresponding Eurostat data[93]. The same information (electricity used for refrigerators, freezers, cooking, microwave ovens and dishwashers) is retrieved for the United States from EIA data[94]. For the rest of the world, the electricity consumption for cooking is calculated for China, India, world average (Eastern Research Group report[91]) and Africa (Africa Energy Outlook from IEA[90]), using region specific data.

We also evaluated the amount of different fuels (for example, gas, oil, solid) burnt in the household sector for cooking relates purposes and calculated the corresponding share to be applied to the residential combustion emissions. Eurostat[93] and EIA[94] data were used for Europe and the United States, while for the rest of the world countries, individual country shares (for example, for China, India, Bangladesh and Uganda) as well as a world average share are computed to estimate the fraction of household emissions associated with the food system based on the Eastern Research Group report[91]. Overall, $SFS_{s,c,t}$ for the household sector ranges (minimum–maximum) between 0.003 and 0.265.

End of life. The end-of-life stage includes emissions from solid waste disposal and waste water treatment, as discussed in detail below.

Solid waste disposal. Emissions from solid waste disposal from the food system are related to the incineration (without energy recovery) of biogenic waste, incineration of industrial solid, municipal solid waste, non-specified waste and of sewage sludge, waste disposal on landfills and composting (SFS = 1). The organic fraction of the municipal waste for each world country/region has been extracted from the World Bank *What a Waste* report[95]. We assumed that the organic biomass fraction in solid waste is predominantly associated with food systems, while the non-organic fraction is not predominantly associated with food systems. We used the low heating value (LHV) of the different components in solid waste as a proxy for the allocation of GHG emissions from waste incineration of the different waste fractions (for example, plastic, paper, organic, glass, other)[95,96]. Due to the lack of detailed data, we could not separate the fraction of food-related waste from the fraction of biogenic waste coming from non-food sources such as gardening and landscape maintenance. This assumption represents an overestimation of this component for industrialized countries in particular, while it can be considered rather reliable for developing regions where the garden and landscape maintenance collection of waste is less common. We considered the impact of our assumption in the uncertainty evaluation of this category, which varies from moderate to high (Supplementary Fig. 2). The shares for solid waste incineration are in the range ($SFS_{s,c}$ minimum–maximum) of 0.026–0.85, while $SFS_{s,c}$ for landfills varies between 0.26 and 0.88.

Waste water. Domestic and industrial waste water almost entirely contribute to food-system emissions. Emissions from domestic waste water are computed separately for rural areas, urban-high-income and urban-low-income countries. The basic activity data, which is the total organically degradable carbon in waste water (TOW), was calculated for rural, urban-high, and urban-low-income populations. The share of rural population within the total population was estimated from the United Nations Department of Economic and Social Affairs (Population Division) data[97]. For urban populations, we used the information provided by the IPCC[98] Supplementary Table 6.5 and data about population in slums from UNHABITAT[99,100] and World Bank[101,102] to distinguish between urban-low-income and urban-high-income. Industrial waste water emissions include the contribution from nitrogen-containing effluents (and sludge), alcohol refining, meat and poultry processing and raw sugar refining (SFS = 1). Industrial waste water emissions associated with pulp production are based on the paper used for food packaging with an $SFS_{s,c,t}$ minimum–maximum range of 0.089–0.439.

Uncertainty analysis. As part of the yearly releases of the updated EDGAR database, comparison with national reporting for main emitters (Europe, the United States and China) is carried out in the context of an internal quality assurance protocol (for CO_2 emissions in particular). More recently, EDGAR emission data for agriculture have been toughly assessed and compared against national reporting emissions during a verification exercise[103] and for all sectors for CO_2 (ref. [104]) and for the complete GHGs[105]. To our knowledge, the calculation of food-system shares has never been done at the level of detail in this Article, so in-depth comparison with independent data was not possible. All shares used, however, were subject of scrutiny and sensitivity analysis (sense making) and were given an added uncertainty due to emissions, as detailed below.

Activity data (AD) and emission factor (EF) uncertainties for anthropogenic activities have been derived from IPCC guidelines[53], while LULUC uncertainty is fixed at 50%[58]. A summary is provided in Supplementary Table 1. Total uncertainty is calculated by the sum of squares for the uncertainty of AD and EF for a given source. The uncertainty of the aggregation levels is calculated by assuming full correlation for fuel type (CO_2) and for sector (CH_4 and N_2O), reflecting the more detailed information provided by IPCC[53] on fuel type uncertainty for CO_2 (assumptions taken, for example, in Bond et al.[106], Bergamaschi et al.[107], Petrescu et al.[103], Choulga et al.[104], and Solazzo et al.[105]). Moreover, developing countries are given higher uncertainties to account for underrepresentation in the data underlying our estimates[53]. A further source of uncertainty is the share factors adopted to account for the portion of GHG emissions stemming from the food system only. As described above, the food-related share of emissions from energy, transport, waste and some chemical and industrial processes is not readily available and assumptions have been made, either per country or for the whole world. Supplementary Table 5 reports these shares by sector and the associated uncertainty.

Supplementary Table 1 presents an overview of the sectors contributing to the food system considered in this work, as well as two sectorial aggregations representing the food chain and food-system structure. A confidence level for the assumed shares representing the food-system contribution to each sector is also provided. High confidence (H) means that the shares applied (for example, $SFS_{s,c,t} = 1$) do not add further uncertainty to the original emissions for that sector. Medium (M) and medium–high (M–H) confidence mean that a rather small (10 to 20%) additional uncertainty is due to the application of the food shares. Low confidence (L) means that the GHG emission uncertainty will be enhanced by up to 100% due to the application of the food shares.

The share of the emissions from the packaging and chemical industries that are devoted to food is highly uncertain because accurate data were not available for this sector. A conservative estimate of 0% (assuming all emissions not related to food) to 100% (all emissions related to food) has been applied. Transportation (road, maritime, air) is also uncertain, because detailed country coverage is not available. Because regional shares were applied worldwide, spatial heterogeneity is not fully captured and an uncertainty of 35% to 75% is applied to account for the lack of representativeness of the share. Solid waste shares are also subject to an additional uncertainty of 5% to 10% due to the methodological assumptions and the LHV proxy discussed above. Supplementary Fig. 3 shows food-system GHG emissions by gas and by sector with the uncertainty estimates from Supplementary Table 1. Supplementary Table 5 reports minimum and maximum uncertainty values for food emission estimates by country and sector.

Data availability

The data that support the findings of this study are available as Excel spreadsheets alongside the paper. Moreover, they are available on the EDGAR website and can be accessed at the following link: https://edgar.jrc.ec.europa.eu/overview.php?v=EDGAR_FOOD. When citing the EDGAR-FOOD dataset, please specify the following link[108]: https://doi.org/10.6084/m9.figshare.13476666. All figures present in the manuscript are also available in figshare under the same doi as the EDGAR-FOOD dataset. Source data are provided with this paper.

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Author contributions

M.C. and D.G. designed and developed the EDGAR-FOOD database; E.S., M.C. and F.M.-F. worked on the definition of food-system shares for all GHG emitting categories; A.L. designed the project, revised the methodology and identified the key messages of the manuscript; F.N.T. provided the FAO data and supported the discussion of the LULUC component; all authors helped in drafting the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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