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*Supplement of*

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

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# SUPPLEMENTARY INFORMATION

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The methods included in this SI should be cited as follows:

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Karl, K. and Tubiello, F.N. 2021b. *Methods for Estimating Greenhouse Gas Emissions from Food Systems*. *Part II: Food Systems Waste Disposal*. FAO Statistics Working Paper 21-28. Rome. Available at: https://www.fao.org/documents/card/en/c/cb7028en

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## 1. Methods to Estimate GHG Emissions by Food Systems Component

The methodology presented in this paper follows a step-wise approach for the estimation of food systems emissions:

S*tep 1* identifies, for each food systems component, the relevant international statistics needed to characterize country-level activity data (AD).

*Step 2* determines the food-related shares of the activity data ($AD_{food}$) and assigns relevant GHG emission factors (EF) to each activity. $AD_{food}$ was set to unity for the food processing and food waste domains.

*Step 3* implements the generic IPCC method for estimating GHG emissions ($E_{food}$), using inputs of activity data and emission factors from the first two steps, as follows:

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

Finally, *Step 4* imputes any missing food systems emissions data by component, using as input PRIMAP, a complete dataset of emissions estimates for all IPCC sectors, by country, over the period 1990-2019 (Gütschow et al., 2021).

### 1.1. Fertilizer Manufacturing

#### 1.1.1 Activity data

*Activity data* were sourced from the FAOSTAT *Fertilizers by Product* Database (FAO, 2021a), which contains data on the amount of different fertilizers produced by country, with global coverage for the period 2002-2019. The following fertilizer products were included: ammonium nitrate; calcium ammonium nitrate; urea; urea ammonium nitrate; ammonium sulfate; anhydrous ammonia; NPK fertilizers; monoammonium phosphate, diammonium phosphate, superphosphates (both above and below 35%); potassium chloride (muriate of potash); and potassium sulfate (sulfate of potash). These categories of fertilizers represent 85% of the total quantity of fertilizer produced over the time period covered by the database (2002-2019). The database covers nearly 200 countries and territories for the period 2002-2019. Missing values for the period 1990-2001 were computed by using linear regression and only applied to countries with annual fertilizer production data in the FAOSTAT *Fertilizers by Nutrient* Database from 1990-2001 (FAO, 2021b). For mainland China, data were sourced from the FAOSTAT *Fertilizers by Nutrient* database, since no product-specific fertilizer data is available for mainland China in the FAOSTAT *Fertilizers by Product* Database.

#### 1.1.2 Food shares

Fertilizers are manufactured worldwide, with agriculture being the largest user. Because of lack of country-level or even regional-level information on final use (FAO, 2021c), a globally-averaged food share coefficient, obtained by dividing world total agriculture use of N fertilizers by world total production of fertilizers N, as disseminated in FAOSTAT, was applied to all countries with information on fertilizer production in FAOSTAT. The global food share coefficient thus obtained varied over time over the period 1990-2019, ranging from 0.88 to 0.98, with a mean of 0.93.

#### 1.1.3 Emission factors

*Emission factors* used were specific to fertilizer products. They were sourced from the International Fertilizer Society (2019) for ammonium nitrate, calcium ammonium nitrate, urea, and urea ammonium nitrate, and from Brentrup et al. (2018) for ammonium sulfate, anhydrous ammonia, NPK fertilizers, monoammonium phosphate, diammonium phosphate, superphosphates (both above and below 35%), potassium chloride and potassium sulfate.

Regional EFs were applied based on product-specific data for: Europe (e.g., EU-27 countries); Commonwealth of Independent State nations (CIS) (e.g., Belarus, Russia, Turkmenistan, Ukraine and Uzbekistan); Africa (e.g., Algeria, Egypt, Nigeria and South Africa); Middle East (e.g., Iran, Kuwait, Oman, Qatar, Saudi Arabia, Turkey and UAE); North America (e.g., USA and Canada); Latin America and the Caribbean (e.g., Argentina, Brazil, Mexico, Trinidad & Tobago and Venezuela); South Asia (e.g., India and Pakistan); South-East Asia (e.g., Indonesia, Malaysia and Vietnam) and Oceania (e.g., Australia and New Zealand, see Table 1). Emission factors for nitrogenous fertilizer production in China were taken from International Fertilizer Society data for nutrient N (IFS, 2018) as an average of coal and gas-based production, and a weighted average across N fertilizer types was based on data from Zhang et al. (2013, Supplemental Figure S1). N fertilizer are produced mainly in China, USA, India and Russia. China, US and Russia and also among the main producers of $P_2O_5$ and $K_2O$ fertilizers. EFs for nutrient $P_2O_5$ and $K_2O$ for China are taken as average values from Brentrup et al., 2016.

**Table 1. Product specific emission factors, indicating ranges across regions.**

| **Product** | **$CO_2$ emissions factor (kg $CO_2$eq/ kg product)** | **$N_2O$ emissions factor (kg $CO_2$eq/ kg product)** | **Sources** |
|---|---|---|---|
| Ammonium Nitrate | 0.77-1.36 | 0.16-1.66 | IFS, 2019 |
| Calcium Ammonium Nitrate | 0.67-1.48 | 0.13-1.34 | IFS, 2019 |
| Urea | 0.57-1.36 | 0 | IFS, 2019 |
| Urea Ammonium Nitrate | 0.53-1.10 | 0.07-0.74 | IFS, 2019 |
| Ammonium Sulphate | 0.56-1.12 | 0 | Brentrup et al., 2018 |
| Anhydrous Ammonia | 2.05-4.2 | 0 | Brentrup et al., 2018 |
| NPK Fertilizers | 0.71-1.71 | 0 | Brentrup et al., 2018 |
| Diammonium Phosphate * | 0.63-1.15 | 0 | Brentrup et al., 2018 |
| Monoammonium Phosphate * | 0.44 -0.81 | 0 | Brentrup et al., 2018 |
| Superphosphate (above 35%) * | 0.18-0.28 | 0 | Brentrup et al., 2018 |
| Superphosphate (below 35%)* | 0.08-0.13 | 0 | Brentrup et al., 2018 |
| Potassium Chloride | 0.25 | 0 | Brentrup et al., 2018 |
| Potassium Sulfate | 0.25 | 0 | Brentrup et al., 2018 |

(*) EFs include energy use in mining and extraction of phosphorous and potassium from parent rock material, which were not separated in the available literature (Hasler et al., 2015).

### 1.2 Food Processing

#### 1.2.1 Activity data

Relevant *activity data* were sourced from the UNSD Energy Statistics Database, ISIC Divisions 15-16, Flow 1214f: Final Energy Consumption by Manufacturing of Food and Tobacco (UNSD, 2021). UNSD data represented official country data from 100 countries and territories. For these, UNSD information was already fairly complete; additional gap-filling performed by FAO—by linearly interpolating in between available years and by carrying forward last available values—led to an overall imputation rate of 6.3%. The UNSD energy data by fuel corresponded to IPCC Energy sector sub-category 1A2e (*Food Processing, Beverages and Tobacco*) including electricity and heat. Finally, the UNSD data, expressed originally in fuel amounts, were converted to energy units by using IPCC (2006) default calorific values or, when the latter were missing, by UNSD and IEA (2004) coefficients.

#### 1.2.2 Food shares

The food share percentage of the UNSD energy data, representing use in food and tobacco processing, was set to unity. This assumed that the tobacco processing component was negligible in comparison to the food component, in line with assumptions made in previous work (Crippa et al., 2021a). As an indirect confirmation of this assumption, FAOSTAT statistics indicated that tobacco represented globally only 0.1% of all crop production in 2019. Explicit analyses of energy use in the manufacturing sectors are otherwise scarce. Two national analyses for the US and the Netherlands confirm nonetheless that energy use in tobacco processing represent a very small percentage of total energy use in food, beverage and tobacco processing (Ramírez et al., 2006).

#### 1.2.3 Emission factors

The GHG emissions from food processing considered here consist of carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) gases emitted by the on-site combustion of fossil fuels for energy generation and the off-site generation of electricity. Default *emission factors* for use in equation (1) above were taken from IPCC (2006), relative to *stationary combustion in manufacturing industries and construction* (Volume 2, Chapter 2, Table 2.3).

Consistently with the same IPCC guidelines, biofuels and renewables were considered carbon-neutral fuels, i.e., their emissions coefficients were assumed to be zero.

For electricity, characterized by energy generated using a mix of fuels, country-specific and year-specific grid $CO_2$ emission factors over the period 1990-2012 were taken from IEA (2013), and carried forward for the period 2013-2019 using the most recent 10-year average. Country-specific heat emission factors were set to 52% of corresponding grid electricity emission factors based on a large synthesis analysis published by the IPCC Fifth Assessment Report (IPCC, 2014; figure A.II.4). $CH_4$ and $N_2O$ emission factors were computed from $CO_2$ emission factors, using methods of the IPCC (2006; Vol. 2 Ch. 3, Tab. 2.2).

The country-level grid emission factors developed for food processing were also applied to the other food systems components of this analysis.

## 1.3. Food Packaging

### 1.3.1 Activity data

Activity data for energy use in industrial production of glass and plastic were taken from the UNSD Energy Statistics Database (UNSD, 2021a), Flow 1214b: Final Energy Consumption by Manufacturing of Non-Metallic Minerals. Activity data for energy use in industrial production of paper were taken from Flow 1214g: Consumption by Pulp, Paper and Print. Activity data for industrial production of tin were taken from the UNSD Industrial Commodity Statistics database (UNSD, 2021b). Finally, data for aluminium production were taken from aluminium industry publications (IAI, 2018). The relevant data on the materials analyzed was available for 215 FAO countries and territories.

### 1.3.2 Food shares

The computation of food shares in packaging proceeded through the following steps:

For *glas*s, the share of energy consumption for glass manufacturing to total energy consumption for all non-metallic minerals production were collected from the literature for the EU, US, and China (see Table 2). First, it was assumed that 19% to 62% of energy use in non-metallic mineral production is associated with glass production (Table 2). The EU estimate of 31% was applied to the rest of the world since the information provided by the referenced reports represent the most spatially comprehensive and detailed data (EU-MERCI, 2017). The share of container glass of total glass production was taken from the literature, and ranged between 30% to 60% (Table 2). The resulting food shares of energy use for non-metallic mineral production ranged between 10% and 19%.

For *plastic*, it was first assumed that 4% energy use (oil and gas) in the chemical industry was for plastics manufacturing globally (IEA, 2018). We then applied a coefficient of 30% to estimate the share of plastics manufactured used for packaging (UNEP, 2018). Finally, we employed a third coefficient of 40% to determine the food share of plastic packaging (ING Economics Department, 2019). The result was a food share of 0.48%.

For *aluminium*, it was assumed that 60% of energy consumption in primary non-ferrous metals production could be attributed to aluminium production (IEA, 2007). Data on aluminium production were available for Europe, Canada, USA, Mexico, Brazil, South Africa, Australia, China, India, Russia and Japan (IAI, 2018). The food share of aluminium production was determined by dividing the amount of aluminium used for aluminium cans and aluminium foil by the total amount of aluminium produced in a year. The year-specific shares ranged between 4% and 38%. The food share percentages of aluminium packaging, obtained by combining information on energy use for aluminium production, the percentage going to packaging, and the food share of that packaging, ranged across countries and regions from 2% to 27% of energy used by non-ferrous metals. Year-specific regional food share averages were developed were calculated according to FAOSTAT definitions and applied to countries with no country-specific food share data but which contained aluminium production data in the UNSD Industrial Commoditiy Statistics database (UNSD, 2021b).

For *tin*, year-specific energy shares of food-related tin production to total iron and steel were based on Tinmill Product Share of Non-Ferrous metals in the World Steel Association's World Steel Statistical Yearbook (WSA, 2019). The methodology assumes that virtually all cans and containers in tinmill products are for food. Taken together, the country-specific and year-specific food shares ranged 1%-9% of energy use in iron and steel production. Year-specific regional food share averages were developed based on the World Steel Association data and applied to countries with tin production data based on the UNSD Industrial Commodity Statistics database (UNSD, 2021b).

For *pulp and paper*, food shares were estimated from information from the FAOSTAT Forestry Products Database (FAOSTAT, 2021c). Here it was assumed that household and sanitary papers are primarily food-related, as well as "cartonboard", which is described as "mainly used in cartons for consumer products such as frozen food and liquid containers" (Eurostat/FAO/ITTO/UNECE, 2020). The fraction of this category over the total aggregate (containing: packaging paper and paperboard, graphic papers, pulp for paper, and wood pulp) was used to determine the food share of energy used for food in pulp and paper production. Country-specific and time-dependent food shares ranged between 1%-50% of total energy used in pulp and paper production, excluding biofuels and renewables.

**Table 2. Share of energy use in non-metallic minerals manufacturing for glass packaging**

| Country or Region | Literature Source | Fuels | Glass share of energy use in non-metallic mineral production | Food share of energy use in glass production | Food share of energy use in non-metallic mineral production |
|---|---|---|---|---|---|
| EU | EU-MERCI, 2017; Scalet et al., 2012; Schmitz et al., 2011; Bergmann et al., 2007; Alliance Europe 2021 | Natural gas, Electricity, Fuel oil* | 0.31 | 0.6 | 0.19 |
| USA | EIA 2013; EIA 2017; EIA 2021 | Natural gas, Electricity | 0.62 | 0.3 | 0.19 |
| China | Hu et al., 2018 | Natural gas, Electricity, Fuel oil, Coal | 0.19 | 0.53 (World figure used) | 0.11 |
| UK | Ireson et al, 2019 | NA | 0.31 (EU figure used) | 0.6 | 0.19 |
| World | IEA. 2007; CARE Ratings, 2018 | NA | 0.31 (EU figure used) | 0.53 | 0.16 |

*includes gas oil and diesel oil

### 1.3.3 Emission factors

As done for other energy use components, emission factors to estimate GHG gas emitted per unit fossil fuel combusted in energy production were the IPCC (2006) default values for *Stationary Combustion in Manufacturing Industries and Construction* (Vol. 2, Ch. 2, Tab. 2.3). Emission factors for renewables were assumed to be zero.

## 1.4. Food Retail

### 1.4.1 Activity data

Activity data of energy use are taken from UNSD Energy Statistics, Flow 1225: Final Energy Consumption in Commerce and Public Services (UNSD, 2021a). Activity data for mainland China, which was not represented in the UNSD database, were taken from IEA energy statistics, Final Consumption in Commercial and Public Services (IEA, 2020). Activity data for F-gas emissions are taken from Crippa et al. (2021a), which contains country- and year-specific data on food-related emissions of HFC 134a, HFC-32, HFC-143, and HFC-125 in accord with IPCC guidelines (IPCC, 2019a, Vol. 3, Ch. 7). Since the data from Crippa et al. (2021a) only extend to 2015, the relationship between food-related emissions and total country emissions were used to extend the data with linear regression from 2015-2019, using the methodology described in depth in Karl and Tubiello (2021a).

### 1.4.2 Food shares

The food share of energy use in retail are taken from a variety of publications sourced from governments and academia (Table 3). For India, Africa, and Latin America food shares were based on Crippa et al. (2021a). Where country or region-specific data was not available, averages based on the country groupings of "Industrialized" and "Developing" where applied to countries in such groups, as displayed below. Country groupings for "Industrialized" and "Developing" countries were applied based on the methodology and groupings employed by Crippa et al. (2021a, Supplementary Table 2).

**Table 3. Energy use in Food Retail**

| Country/Region | Food Shares | Sources |
|---|---|---|
| EU-27 | 0.11 | Eurostat, 2018 |
| USA | 0.06 | USDA, 2017; EIA, 2012 |
| China | 0.08 | Song et al., 2019; IEA, 2015 |
| India | 0.13 | GACC, 2017; MOSPI, 2015; IEA, 2015 |
| Africa | 0.14 | GACC, 2017; PRB 2021; IEA 2015<br>(Average of Kenya, Ghana, Uganda and Nigeria) |
| Latin America | 0.14 | GACC, 2017; PRB 2021; IEA 2015 (Guatemala) |
| Industrialized | 0.08 | Average of EU-27, USA and China |
| Developing | 0.15 | Average of India, Africa and Latin America |

#### 1.4.3 Emission factors

Emission factors to estimate GHG gas per unit fossil fuel combusted in energy production were the IPCC (2006) default values for *Stationary Combustion in the Commercial/Institutional Category (*Vol 2., Ch. 2, Tab. 2.4). Emission factors for renewables were assumed to be zero, and emissions from biofuels were excluded in this analysis.

### 1.5. Household Consumption

#### 1.5.1 Activity data

Activity data for industrial production were taken from UNSD Energy Statistics, Flow 1231: Consumption by households (UNSD, 2021a). UNSD data represented official country data from 238 countries and territories. Additional gap-filling was performed by FAO by linearly interpolating in between available years and by carrying forward last available values. This led to an overall imputation rate of 2.6%. The UNSD energy data by fuel corresponded to IPCC Energy sector sub-category 1A4b (*Residential*) including electricity and heat. As for other food system components, the UNSD data, expressed originally in fuel amounts, were converted to energy units by using IPCC (2006) default calorific values or, when the latter were missing, by UNSD and IEA (2004) coefficients.

#### 1.5.2 Food shares

The food share of energy use in households can be considered as the sum of the cooking share of energy use in households, the refrigeration share of energy use in households and the energy use of appliances (e.g., dishwasher, microwave). Food shares were collected from a variety of literature sources including academic journals, government publications, and international organization reports (Tables 4 and 5). Whenever possible, cooking and refrigeration shares of energy use in households were collected separately. For countries and territories where data are not available, we calculated regional averages according to FAOSTAT definitions, and applied the resulting food shares to those countries. The resulting food shares were then applied to the UNSD activity data.

**Table 4. Food shares (cooking) for household energy consumption by country and region**

| Country or region | Food Share (Cooking) | Source |
|---|---|---|
| Africa | 0.31 | Calculated regional average. |
| Albania | 0.27 | EUROSTAT, 2019 |
| Argentina | 0.17 | Zabaloy et al., 2020 |
| Asia | 0.30 | Calculated regional average. |
| Australia | 0.06 | IEA, 2016 |
| Bosnia and Herzegovina | 0.05 | EUROSTAT, 2019 |

| | | |
|---|---|---|
| Brazil | 0.55 | Coelho et al., 2014 |
| Canada | 0.04 | IEA, 2016 |
| China, mainland | 0.40 | Zheng and Wei, 2016 |
| EU27 | 0.06 | EUROSTAT, 2019 |
| Europe (excl. EU27) | 0.10 | Calculated regional average. |
| Guatemala | 0.18* | Pachauri et al., 2018 |
| India | 0.63 | EIA, 2014 |
| Japan | 0.08 | IEA Energy Efficiency Indicators 2016 |
| Latin America and the Caribbean | 0.44 | Calculated regional average. |
| Mozambique | 0.17* | IEA, 2019 |
| New Zealand | 0.06 | IEA, 2016 |
| Nicaragua | 0.58* | Pachauri et al., 2018 |
| Nigeria | 0.43 | Gujba et al., 2015 (calculated) |
| North America | 0.03 | Calculated regional average. |
| Norway | 0.02 | EUROSTAT, 2019 |
| Oceania | 0.06 | Calculated regional average. |
| Republic of Korea | 0.08 | IEA, 2016 |
| Republic of Moldova | 0.13 | EUROSTAT, 2019 |
| Serbia | 0.07 | EUROSTAT, 2019 |
| Turkey | 0.08 | IEA, 2021 |
| Ukraine | 0.16 | EUROSTAT, 2019 |
| United Kingdom | 0.03 | EUROSTAT, 2019 |
| United States of America | 0.02 | EIA, 2015 |

*Does not include biofuels.

**Table 5. Food shares (refrigeration) for household energy consumption by country and region**

| Country or region | Food Shares (refrigeration) | Source |
|---|---|---|
| Asia | 0.23 | Calculated regional average. |
| Australia | 0.07 | IEA, 2016 |
| Austria | 0.03 | IEA, 2016 |
| Canada | 0.03 | IEA, 2016 |
| China, mainland | 0.02 | Zheng and Wei, 2016 |
| Czech Republic | 0.03 | IEA, 2016 |
| Denmark | 0.02 | IEA, 2016 |
| Europe | 0.03 | Calculated regional average. |
| Finland | 0.02 | IEA, 2016 |
| France | 0.04 | IEA, 2016 |
| Germany | 0.03 | IEA, 2016 |

| | | |
|---|---|---|
| Greece | 0.09 | IEA, 2016 |
| Ireland | 0.02 | IEA, 2016 |
| Italy | 0.03 | IEA, 2016 |
| New Zealand | 0.03 | IEA, 2016 |
| North America | 0.03 | Calculated regional average. |
| Oceania | 0.05 | Calculated regional average. |
| Portugal | 0.02 | IEA, 2016 |
| Slovak Republic | 0.04 | IEA, 2016 |
| Sweden | 0.01 | IEA, 2016 |
| Switzerland | 0.03 | IEA, 2016 |
| Republic of Korea | 0.03 | IEA, 2016 |
| United Kingdom | 0.03 | EUROSTAT, 2019 |
| United States of America | 0.03 | EIA, 2015 |
| World | 0.03 | Calculated average. |

As a subsequent step to further refine the GHG emissions from food consumption, only the relevant fossil fuels (kerosene, LPG, natural gas) and electricity have been retained for the calculation of the GHG emissions. In the calculation, the food shares were adjusted accordingly so that the total energy used for food consumption in each country did not change.

### 1.5.3 Emission factors

The emission factors used follow IPCC guidelines in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Default Emission Factors for Stationary Combustion in the Residential Category (IPCC, 2006, Vol 2. Ch 2., Tab. 2.5).

## 1.6 Food Transport

Emissions from food transport can be estimated at the country-level, using the basic formula:

$Emissions = (F_i / T_i) * E_i$

where:

*Emissions* = Gigagrams $CO_2$ equivalents (Gg $CO_2$e $yr^{-1}$)

*F* = Energy used in Food Transport in select country or region, *i*,

Quadrillion BTU $yr^{-1}$ (qBTU $yr^{-1}$),

or

Million tons of oil equivalents $yr^{-1}$ (Mtoe $yr^{-1}$)

*T* = Total energy used in all domestic Transport in select country or region, *i*,

Quadrillion BTU $yr^{-1}$ (qBTU $yr^{-1}$),

or

Million tons of oil equivalents $yr^{-1}$ (Mtoe $yr^{-1}$)

*E* = Emissions from Transport in select country or region, *i*,

Gigagrams $CO_2$ equivalents $yr^{-1}$ (Gg $CO_2$e $yr^{-1}$)

### 1.6.1 Activity Data

Activity data for the United States, China and the European Union are estimated from three sources that contain specific information on the energy used in food distribution in those economies (Table 6). These figures are then applied as a fraction of total energy use to determine the fraction of total transportation emissions that are attributable to food distribution in those areas in the relevant years. The transportation activity in these three economies represents 50.4 percent of all global domestic transportation emissions according to the PRIMAP-HIST Third Party Reported dataset (Gütschow *et al*., 2021). Using economy-specific estimates for food transport in these three economies is therefore a significant advancement in the effort to quantify global emissions from domestic food transport.

**Table 5. Food share of domestic transport in key countries**

| Region | Unit | Food Transport ($F_i$) | Total Transport ($C_i$) | Food share ($F_i$)/ ($C_i$) |
|---|---|---|---|---|
| USA | qBTU $yr^{-1}$ | 0.8[1] | 26.1[2] | 3.1% |
| China | Mtoe | 10.8[3] | 238.5[4] | 4.5% |
| EU27 | Mtoe | 23.4[5] | 305.0[6] | 7.7% |

$CO_2$eq emissions from food transport in the United States, China, and European Union can then be applied as a fraction of total domestic transport emissions in PRIMAP-hist dataset, including fractions of PRIMAP-hist totals for $CH_4$ and $N_2O$ emissions reported as part of the IPCC domestic transport category, IPC1A3 (Gütschow *et al.*, 2021). Since this dataset currently extends to 2019, the food share of total domestic transportation emissions can be used to estimate food transport GHG emissions to 2019.

[1] USDA, 2017
[2] EIA, 2020
[3] Song *et al.* 2019
[4] IEA, 2015
[5] JRC, 2015
[6] IEA 2015

The food share of total domestic transportation for other countries can be estimated using EDGAR-FOOD data, provided by Crippa *et al*. (2021a), which estimates total food system emissions for each country, as well as the fraction of those emissions attributable to food transport (see Supplementary Table 7). Here, the authors rely on rough global averages for country-specific estimates, and note a low-level of confidence for their estimates (Crippa *et al*., 2021a; based on FAO, 2011 and FAO, 2015).

Given that the data is provided with a low level of confidence (see Crippa *et al*., 2021a, Supplementary Table 2), it is preferable to prioritize data from country- and region-specific studies, and use EDGAR-FOOD data secondarily where that does not exist. Our methodology therefore suggests prioritizing administrative data and county-specific data from peer-reviewed studies (such as those used in section 3) before relying on the EDGAR-FOOD dataset. This is especially important for estimating emissions from the U.S., China and E.U., given the magnitude of the emissions generated in those economies.

The EDGAR-FOOD data on food transport emissions does not extend beyond 2015 (Crippa *et al*., 2021a). However, food transport emissions outside beyond the timespan of that dataset can be estimated by extrapolating a trendline from the data that exists. Once the fraction of each country's total domestic transportation emissions that are attributable to food transport (i.e., the "food share") for each year is calculated, the interannual changes in the food share can be used to fit a linear trendline.

**1.6.2 Food shares**

To estimate the food share for 2016-2019, we propose using food transport emissions from EDGAR-FOOD (Crippa *et al*., 2021b), applied as fraction of annual total domestic transportation emissions from the PRIMAP-hist database (Gütschow *et al*., 2021) to extrapolate a trendline from the previous decade (2006-2015). Given that there appears to be only moderate fluctuation in the food share time series data, a simple linear regression is suitable for this estimation. This method can project the food share for years not covered by the dataset, which can then be applied to PRIMAP data from domestic transportation emissions (Gütschow *et al*., 2021) for years 2016-2019.

Therefore, emissions from food transport before 1990 and after 2015 can be estimated at the country-level, using the basic formula:

$Emissions_{i,y} = FS_{i,y} * TTE_{i,y}$

where:

*Emissions* = emissions from food transport for select country i, for year, y, Gigagrams $CO_2$ equivalents (Gg $CO_2$e $yr^{-1}$)

*FS* = estimated fraction of total domestic transport emissions attributable to food (i.e., food share) in country or region, *i*, in the inventory year, *y*,[7]

*TTE* = domestic food transport emissions in select country, *i*, for select inventory year, *y*, Gg $CO_2$e $yr^{-1}$.[8]

**1.7 Food Waste**

**1.7.1 Activity Data for Methane Emissions from Solid Food Waste in Landfills**

Activity data can be estimated from two main inputs— the *World Bank What a Waste Report 2.0,* which contains data on the total amount of waste deposited per country, and the Intergovernmental Panel on Climate Change (IPCC) 2019 Refinement, which contains data on the percentage of waste sent to landfills and open-dumps, as well as the fraction of municipal solid waste that is food waste (Kaza *et al.*, 2018; IPCC, 2019 Vol. 5 Ch.2 Table 2A.2). Where country data for the percentage of food waste and fraction of waste that is open-dumped and landfilled do not exist, regional means can be applied as set forth in the 2019 Refinement, Vol. 5, Ch. 2, Table 2A.1 (IPCC, 2019). Taken together, the World Bank/IPCC data provide information on specific modes of food waste disposal by country, for the year 2016, i.e., the amounts of solid food waste disposed to landfills and open-dumps. This is the information needed to estimate GHG emissions, through decay of disposed organic matter. It is noted that a new database on food waste was recently developed by the United Nations Environment Programme (UNEP, 2021), by country, for the year 2019. While the new UNEP data are not yet useful to compute GHG emissions, since they focus on food waste generation rather than disposal, FAO has already provided input to UNEP to include specific waste disposal information in their future data collection efforts. At that point, UNEP data can be integrated with those from the World Bank, used herein, to enrich and further improve our estimates.

[7] Based on Crippa *et al*., 2021b and Gütschow *et al*., 2021
[8] From Gütschow *et al*., 2021

The organic matter of solid food waste decays over time, with a half-life estimated between 1.7 and 11.6 years, depending on climatic conditions, landfill site conditions, and the composition of the food being wasted (Brown, 2016; IPCC, 2019). In order to estimate GHG emissions from landfilled food waste in a current year, it is necessary also estimate how much food was deposited in landfills 10, 20, and even 30 years ago, which will continue to decay in the year of inventory. However, much of the current data that exists on solid food waste are limited to observations in single year, such as the data collected in the recent Food Waste Index 2021 report from UNEP (2021), or the World Bank's *What a Waste Report 2*.0, which normalizes country-level waste data to the year 2016 (Kaza *et al.*, 2018).

The decay rate of methane generated from organic waste disposed in a certain year is approximated using a First Order Decay model. Default IPCC values are used for climate-specific decay reaction constants (k-values) in the First Order Decay Model, found in Vol. 5, Ch.3, Table 3.3 (IPCC, 2019). Averaged reaction constants are used for countries where more than one IPCC climate zone apply, according to IPCC climate zone groupings found in the IPCC 2019 Refinement Waste Model spreadsheet (IPCC, 2019).

The decay model is built on an exponential factor that takes as input the estimated degradable organic carbon fraction and the decomposable organic carbon fraction of food waste. Default IPCC values are used for the degradable organic carbon fraction (i) and the decomposable degradable organic carbon fraction (ii).

(i) The degradable organic carbon fraction used is 0.15 as found in Vol. 5, Ch. 2 Tab 2.4 (IPCC, 2006).

(ii) The fraction of degradable organic carbon which decomposes for food used is the default value of 0.7 as found in Vol. 5 Ch. 3, Tab. 3.0 (IPCC, 2019).

### 1.7.2 Emissions Factors for solid food waste in landfills

Emissions factors are estimated at Tier 1 using IPCC guidelines, continuing to follow the First Order Decay model set out in Vol. 5, Ch. 2 (IPCC, 2006). Default values are used for methane correction factor (i), oxidation factor (ii), recovery rate (iii), and fraction of anaerobic carbon that is emitted as methane (iv).

(i) The methane correction factor used for all countries is the default weighted average of 0.71 across waste sites, given in the IPCC 2019 Refinement Waste Model annexed spreadsheet (IPCC, 2019).

(ii) The default value used for oxidation factor here is 0, as found in Vol. 5 Ch. 3, Tab. 3.2 (IPCC, 2019).

(iii) The default value for methane recovery rate is 0, as given in Vol. 5, Ch.3 pg. 3.17 (IPCC, 2019).

(iv) The fraction of anaerobic decomposable degradable carbon that results in $CH_4$ is 0.5 as set forth in Vol. 5 Ch. 3, Tab. 3.5 (IPCC, 2019).

Using the back-casted activity data and IPCC emissions factors described previously, it is possible to estimate GHG emissions from accumulated solid food waste deposited in landfills in a given inventory year. Averages of country-level GHG emissions data from solid food waste disposal can then be compared against total solid waste sector GHG emissions. This ratio can then be directly applied to PRIMAP-hist country-level time series data, which includes country-level estimates for $CH_4$ emissions from the IPCC Solid Waste sector dating back to 1850.

This methodology assumes that FAO solid food waste disposal estimates stay relatively constant as a fraction of total solid waste emissions over time, which is evidenced at the global level in figure 2. One reason for the relatively constant ratio of solid food waste disposal emissions to total solid waste sector emissions may be because the effect of per-capita GDP changes on solid waste generation are already captured in the emissions data expressed in the PRIMAP-hist Third party-reported dataset.

Decadal averages of this ratio can be developed for each country over the time series and then applied to each country's annual solid waste sector emissions in each of the three decades of the time series in order to develop regional and country-specific estimates for emissions from solid food waste disposal from 1990 to 2019. This methodology enables solid food waste emissions estimates to follow a similar trajectory as the country-specific trends in total solid waste disposal emissions.

### 1.7.3 Activity Data for Methane Emissions from Domestic Wastewater

Activity data are calculated from World Bank population data, as well as IPCC data on intra-country income and urbanization levels (Vol. 5 Ch. 6 Table 6.5), default treatment/discharge pathway fractions for domestic wastewater for each income and urbanization group (Vol. 5 Ch. 6 Table 6.5), and country-level statistics on per capita biochemical oxygen demand (BOD) found in Vol. 5 Ch. 6 Tab. 6.4 (IPCC, 2019).

Where country-level data for urbanization and income groups and per capita biological oxygen demand do not exist, regional means are applied based on the regional groupings in Vol. 5, Ch. 2 Table 2A.1 (IPCC, 2019). If there are no regional values available based on these regional groups, then larger group means are applied as set forth in the country grouping found in Vol. 5, Ch. 6 Table 6.4 (IPCC, 2006).

The fraction of organics in wastewater removed as sludge and through biochemical decomposition is applied to each country per urbanization and income brackets and provided for septic systems (i), latrines (ii), and sewage systems (iii) using the following values from Vol. 5 Ch. 6, Tab. 6.6B (IPCC, 2019):

(i) Septic tank/septic system: 0.625

(ii) Latrines: 0.7 in wet climates, according to previously defined IPCC climate zones. 0.3 in dry climates, as an average of family and communal use default values.

(iii) Sewage systems: 0.638 as an average of primary treatment and advanced treatment systems.

### 1.7.4 Emissions Factors for Methane Emissions

Emissions factors are calculated at Tier 1 using IPCC guidelines in the 2019 Refinement (IPCC, 2019). Emissions factors, in kg $CH_4$/kg BOD, are used for sewer systems (i), septic systems (ii), latrines (iii), and undefined discharge pathways (iv).

The following emissions factors are taken from Vol. 5 Ch. 6, Tab. 6.3, and measured in kg $CH_4$/kg BOD (IPCC, 2019):

(i) An emissions factor of 0.193 is used for sewage systems, representing the average of effluent emissions for flowing and stagnant sewers (0.15) and average emission factor for primary treated sewage from plants and untreated sewage (0.043).

(ii) An emissions factor of 0.3 is used for septic systems.

(iii) An emissions factor of 0.18 is used for latrines in dry climates (averaging between family and communal latrines), and 0.42 for wet climates according to previously defined IPCC climate regions.

(iv) The default emission factor for undefined discharge and treatment pathways is 0.068.

### 1.7.5 Activity Data for Nitrous Oxide Emissions from Domestic Wastewater

Activity data using from World Bank population data, as well as IPCC data on intra-country income and urbanization levels (IPCC, 2019, Vol. 5 Ch. 6 Table 6.5), default treatment/discharge pathway fractions for domestic wastewater for each group (IPCC, 2019, Vol. 5 Ch. 6 Table 6.5), regional data on protein consumed as fraction of protein supply (IPCC, 2019 Vol. 5 Ch. 6 Tab. 6.10A), regional data on food non-consumed in case food waste is disposed to sewers (IPCC, 2019 Vol. 5 Ch. 6 Tab. 6.10A), and FAOSTAT data on protein supply in the New Food Balances dataset (2014-2017) and Food Balance (old methodology and population) dataset (1990-2013).

Where country data for urbanization and income groups, protein supply, and protein consumption of supply do not exist, regional means are applied based on regional groupings in Vol. 5, Ch. 2 Table 2A.1 (IPCC, 2019). If there are no regional values based on aforementioned regional groups, then larger group means are applied as set forth in the country groups found in Vol. 5, Ch. 6 Table 6.4 (IPCC, 2006).

### 1.7.6 Emissions Factors for Nitrous Oxide Emissions from Domestic Wastewater

Emissions factors are calculated at Tier 1 using IPCC guidelines in the 2019 Refinement (IPCC, 2019). Emissions factors, in kg $N_2O$ - N/kg N, are used for sewer systems (i), septic systems (ii), latrines (iii), and other discharge pathways (iv).

All of following emissions factors are taken from Vol. 5 Ch. 6, Tab. 6.8A, and measured in kg $N_2O$ - N/kg N (IPCC, 2019):

(i) An emissions factor of 0.0105 is used for sewage systems, representing the average emission factor for untreated and primary treated waste fates.

(ii) An emissions factor of 0.0023 is used for septic systems, representing the average emissions factor for septic tanks and septic tanks with land dispersal fields.

(iii) An emissions factor of 0 is used for latrines.

(iv) The default emission factor for undefined discharge and treatment pathways is 0.005.

### 1.7.7 Activity Data for Industrial Wastewater

Activity data for industrial production are taken from the United Nations Industrial Commodity Statistics database, FAOSTAT Crops Processed data, FAOSTAT Livestock Processed data, and FAOSTAT Forestry Production data. When FAOSTAT data and United Nations Industrial Commodity Statistics data cover the same industrial products in the same year for the same country, preference is given to FAOSTAT data. While data for processed food commodities are largely FAO estimates rather than country official data, they represent the state of the art in terms of available information with global coverage.

Data on wastewater generation for each industrial category, as well as chemical oxygen demand per cubic meter of wastewater in each industrial category are taken from Vol. 5 Ch. 6, Tab. 6.9 (IPCC, 2006) and Vol. 5. Ch. 6 Tab. 6.12 (IPCC, 2019). For years where there are gaps in inventory data, missing values are imputed using linear interpolation as appropriate (i.e. in the middle of a series, where the country is still reporting GDP in that year).

Total organics in wastewater (kg COD) is a product of the total output per industrial sector (tons), the amount of wastewater generated per ton of product ($m^3$ $ton^{-1}$), and the chemical oxygen demand (otherwise known as the industrial degradable organic component in wastewater, kg COD / $m^3$).

### 1.7.8 Emissions Factors for Industrial Wastewater

Emissions factors employed follow Tier 1 using IPCC guidelines in the 2019 Refinement, specifically, 0.028 kg $CH_4$/kg COD, as found in Vol. 5 Ch. 6, Tab. 6.3 (IPCC, 2019).

### 1.7.9 Activity Data for Industrial Wastewater

Activity data and data on wastewater treatment are taken from the same sources as stated above for estimating methane emissions from industrial wastewater. Data on wastewater generation for each industrial category, as well as total nitrogen per cubic meter of wastewater in each industrial category are taken from Vol. 5 Ch. 6, Tab. 6.9 (IPCC, 2006) and Vol. 5. Ch. 6 Tab. 6.12 (IPCC, 2019).

Total nitrogen (kg N) is a product of the total output per industrial sector (tons), the amount of wastewater generated per ton of product ($m^3$ $ton^{-1}$), and the total nitrogen in wastewater (kg/ $m^3$).

1.7.10 Emissions Factors for Industrial Wastewater

Emissions factors employed follow Tier 1 using IPCC guidelines in the 2019 Refinement, specifically, 0.005 kg $N_2O$ - N/kg N (Vol. 5, Ch. 6, Tab. 6.8A)

### 1.7.11 Activity Data for Incineration of Plastic and Rubber

Activity data are estimated from the *World Bank What a Waste report 2.0,* which contains data on the total amount of waste deposited per country in 2016, as well as the fraction of total waste that either plastic or rubber waste. Other data inputs are taken from the IPCC 2019 Refinement, which contains country-level statistics and regional defaults on the fraction of waste incinerated (IPCC 2019, Vol. 5, Ch. 2 Table 2A.1). Where country data for plastic and rubber waste fraction and fraction of waste that is incinerated do not exist, regional means are applied as set forth in IPCC 2019, Vol. 5, Ch. 2 Table 2A.1. Where there are no applicable regional means according to these groupings, the fraction of waste incinerated is assumed to be zero. Given the lack of reliable statistics on the quantity of open-burned plastic and rubber, this methodology focuses only on countries with incineration facilities (IPCC, 2019).

### 1.7.12 Emissions Factors for Incineration of Plastic and Rubber

Emissions factors employed depending on the waste type and carbon content specific to each type, as set forth in Vol. 5 Ch. 2 Tab. 2.4 (IPCC, 2006).

Food-related plastic waste incinerated (Gg) is multiplied by dry matter content in percent of wet weight (100 percent), total carbon content in percent of dry weight (75 percent), and fossil carbon fraction in percent of total carbon (100 percent).

Food-related rubber incinerated (Gg) is multiplied by dry matter content in percent of wet weight (84 percent), total carbon content in percent of dry weight (67 percent), and fossil carbon fraction in percent of total carbon (20 percent).

The default conversion factor of 3.67 is then applied to convert from Gg fossil C to Gg $CO_2$ (IPCC, 2006: Vol. 5, Ch. 5 Eq. 5.1). The default oxidation factor used is 100 percent (IPCC, 2006, Vol. 5, Ch. 5, Tab. 5.2).

**2. Imputation of Missing Countries**

The methods applied above allowed for the estimation of food systems emissions for countries and time periods for which activity data were available and relevant food shares could be computed, following steps 1-3. For countries with no activity data, food systems emissions were estimated using an independent global database of emissions data (PRIMAP). The PRIMAP data (Gütschow et al., 2021) provide GHG emissions by country, including from official reporting over the period 1990-2019. PRIMAP also provides a complete 1990-2019 time series of emissions for the IPCC sectors not already covered by FAO: *Energy*, *Industry*, *Waste* and *Other*, covering all FAOSTAT countries. As such, PRIMAP data are used in FAOSTAT (Emissions shares domain) to complement GHG emissions on agricultural land (FAO, 2019). PRIMAP is well-regarded international in addition to its use in FAOSTAT. It was used by the IPCC Special Report on Climate Change and Land (IPCC, 2019b) to estimate food systems emissions shares in total GHG emissions. More recently, PRIMAP data were used by the UNFCCC to assess world-total GHG emissions in a landmark synthesis report (UNFCCC, 2021). With the above in mind, our imputation steps were as follows.

I. For each food systems component, year and sub-region, the average share of emissions in total energy emissions (from PRIMAP) was computed;

II. The average sub-regional share computed above was then applied to PRIMAP energy emissions data for all missing countries in the region, to obtain an estimate of emissions by food systems component, year and country;

An overview of the number of imputed countries is presented in Table 8.

We therefore used the complete set of PRIMAP country energy emissions data as ''prior information'' to constrain and then estimate GHG emissions generated by food systems component, by country and year. This imputation was therefore performed directly at the level of emissions data, without having to gap-fill missing information on energy use in the input databases (i.e., in the activity data). Another advantage of this methodology is that it allowed to estimate time-dependent emissions share factors as opposed to constant coefficients over the period 1990-2019, providing a more realistic approach that better reflects the evolution of food systems and their relation to total energy use in countries.

**Table 8. Gap filling of countries with no activity data**

| **Food system component** | | **No. of FAO countries and territories by AD to calculate GHG emissions** | **Total No. of FAO countries and territories with derived GHG emissions (2019)** |
|---|---|---|---|
| Food processing | | 125 | 72 |
| Fertilizers manufacturing | | 74 | 0 |
| Food packaging | Aluminium | 80 | 74 |
| | Glass | 55 | |
| | Plastic | 114 | |
| | Tin | 107 | |
| | Pulp and Paper | 81 | |
| Food Retail | | 222 | 13 |
| Household Consumption | | 223 | 4 |

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