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PART I: DOMESTIC FOOD TRANSPORT

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METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS
PART I: DOMESTIC FOOD TRANSPORT

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Abstract

This paper is the first in a series of ongoing and planned efforts to build on current knowledge and develop methodologies for estimating new components of food systems emissions, with a view to disseminate the information in FAOSTAT. It provides a methodology for estimating the GHG emissions associated with historic and current domestic food transport, in an effort to inform countries of the environmental impact of their food distribution systems. Based on the methodology, we build a new database of the annual carbon footprint of food transport, on a country basis and with global coverage, for the period 1990-2019.

Our efforts help to better characterize food systems and the role they can play in achieving the Sustainable Development Goals. In particular, they align well with Goal 12 to ensure “sustainable consumption and production patterns’’, specifically Target 12.2, “achieve the sustainable management and efficient use of natural resources” and Indicator 12.2.1, which monitors the “material footprint, material footprint per capita, and material footprint per GDP” of different products.

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1 Introduction

FAO disseminates estimates of country-level greenhouse gas (GHG) emissions from agriculture, in relation to both crop and livestock production activities within the farm gate and land conversion from natural ecosystems (FAO, 2021). The FAO estimates, widely used worldwide, support the high-level synthesis reports produced at regular intervals by the Intergovernmental Panel on Climate Change (IPCC), helping to quantify the contribution of agriculture to total anthropogenic emissions, currently estimated at 20 percent (IPCC, 2019). At the same time, there is limited data availability on, but significantly growing demand for, GHG emissions generated from food systems (Clark *et al*., 2018; Niles *et al*., 2018; Fanzo *et al.*, 2021). New data are therefore needed to characterize processes and emissions generated by food beyond the farm boundary, i.e. arising from additional pre- and post-production activities such as industrial fertilizer production, food processing, food transport, retail and waste disposal (Rosenzweig *et al*., 2020). The most recent efforts in this area of work, developed with significant FAO contribution (Crippa *et al.*, 2021; Tubiello *et al.*, 2021), can serve as a useful basis for exploring how to extend the current FAOSTAT emissions estimates to a fuller food system boundary.

This paper is the first in a series of ongoing and planned efforts to build on current knowledge and develop methodologies for estimating new components of food systems emissions, with a view to disseminate the information in FAOSTAT. It provides a methodology for estimating the GHG emissions associated with historic and current domestic food transport, in an effort to inform countries of the environmental impact of their food distribution systems. Currently, no database estimates recent time series of the annual carbon footprint of food transport, on a country by country basis.

A recent study provided country-level data on GHG emissions from across the food system, including from food transport (Crippa *et al*., 2021a). There, the country-level data on emissions from food transport are predominantly based on rough global averages derived from two FAO reports: "*Energy-Smart" Food for People and Climate* (FAO, 2011) and *Food Wastage Footprint & Climate Change* (FAO, 2015). While the resulting EDGAR-FOOD dataset (Crippa *et al*., 2021b) is an important step forward in the quantification of GHG emissions from food transport at the global level, it could be greatly improved through the inclusion of more country-specific factors. Furthermore, the dataset is limited in temporal coverage, as it only spans the years 1990–2015.

Our efforts help to better characterize food systems and the role they can play in achieving the Sustainable Development Goals. In particular, they align well with Goal 12 to ensure "sustainable consumption and production patterns'', specifically Target 12.2, "achieve the sustainable management and efficient use of natural resources" and Indicator 12.2.1, which monitors the "material footprint, material footprint per capita, and material footprint per GDP" of different products.

In this work, we first delineate the importance of food transport (section 2), then detail a new methodology to derive country-level estimates of GHG emissions from domestic food transport (sections 3 to 5). Finally, we identify limitations to the methodology and discuss alternative approaches, with recommendations for further investigation (section 6).

2 Food transport in context

2.1 Food transport and environmental sustainability

Global food security requires, among other factors, a robust food distribution system that efficiently matches food supply and demand in all countries (D'Odorico et *al.,* 2014). While improving the distributional range and efficiency of food transport is a key food system objective, environmental constraints must also be considered. In particular, the contribution of food transport to climate change must also be addressed, in part because climate change poses a serious threat to global food security in turn (Rosenzweig *et al*., 2020).

A recent study found that global GHG emissions from food systems were approximately 18 billion tonnes (Gt) in 2015, or 34 percent of the global total, and that food transport contributed 0.86 Gt of GHG emissions in 2015, for roughly 5 percent of food system emissions (Crippa *et al*., 2021a). A meta-analysis of life cycle assessments examining the GHG emissions associated with specific agricultural goods had similar findings, estimating that food transport accounts for approximately 6 percent all food system emissions, excluding emissions from waste disposal and household consumption (Poore and Nemecek, 2018).

The transportation share of the total carbon footprint was found to vary widely across commodities. In particular, fresh produce such as root vegetables, bananas, citrus and apples – which have a relatively small carbon footprint overall – were estimated to have a mean transportation share between 25 percent and 45 percent of total embodied emissions (Poore and Nemecek, 2018). At the same time, the transportation share of all GHG emissions use to produce and distribute animal-sourced products was between 1 percent and 5 percent (Poore and Nemecek, 2018).

Indeed, the GHG emissions of producing food are often much greater than the GHG emissions associated with transporting it, a phenomenon that extends beyond animal-source products. Agricultural production emissions are on average 8–10 times higher than transportation emissions for items such as maize, peas and olive oil (Poore and Nemecek, 2018). Further complicating the issue, some agricultural products may be associated with fewer emissions when they are grown further away from where they are ultimately consumed. For example, tomatoes consumed in the United Kingdom of Great Britain and Northern Ireland (UK) would have a smaller carbon footprint if grown in the warmer climate of Spain and transported to the UK, rather than being produced locally in energy-intensive heated greenhouses (Webb *et al.,* 2013).

The transportation mode is a key factor in determining the GHG emissions associated with transporting food. An FAO analysis on energy in the food system found that rail transport comprises 29 percent of global food transport, with an energy intensity of 8–10 megajoules per tonne per kilometre (MJ t^{-1} km^{-1}), while aviation, which has an energy intensity of 100–200 MJ t^{-1} km^{-1}, only accounts for only 1 percent of global transport (FAO, 2011). Furthermore, the analysis found that marine shipping, inland waterway and road trucks are responsible for 29 percent, 13 percent and 28 percent of all global food transport by mass, with energy intensities of 10–20, 20–30, and 70–80 MJ t^{-1} km^{-1}, respectively (FAO, 2011). Owing to the fact that the majority of food transport occurs domestically – and that maritime shipping has a relatively low emissions intensity – Crippa *et al.* estimated that, of the 0.86 Gt of GHG emissions associated with food transport in 2015, only 2.5 percent were due to international shipping and aviation (Crippa *et al.,* 2021b).

2.2 Social, economic and physical challenges in food transport

A variety of factors complicate global food distribution, such as the presence of conflict and political instability, as well as the existence of good institutions for supply chain governance (D'Odorico et *al.,* 2014). In addition, inefficiencies in local and regional transportation systems can also hinder efforts to achieve food security. In some countries, for example, transport and logistics costs can be as high as 60 percent of the market price of a food item, which can in turn make it difficult for food distributors to import or export food at competitive prices on the international market (McCarthy *et al.,* 2018). In countries with poorly developed transportation infrastructure (both physical and digital), inefficiencies in food transport can also lead to higher consumer prices (McCarthy *et al*., 2018). Agricultural products also tend to have a relatively high weight-to-value ratio, which can present further economic challenges to distributors (Wakeland *et al.,* 2012).

In addition to economic challenges, a number of physical constraints can complicate food transport. Food supply chains are long and complex and agricultural production must often reach the consumer within a relatively short window of time. Many food items are highly perishable and damage easily, and rely on a chain of refrigerated distributional modes (i.e. a "cold chain") to reach the consumer with a reasonably stable shelf-life and without posing adverse health risks (Wakeland *et al.*, 2012). For this reason, some food items, such as berries – which have an especially small window of marketability – are often air freighted, which is the most emissions-intensive form of transport. (Wakeland *et al.*, 2012). Food transport must also contend with the unique packaging requirements of individual products, many of which are ideally stored at different temperatures and at different relatively humidity levels (Wakeland *et al.*, 2012).

2.3 Food transport as an important piece of the food systems emissions puzzle

Quantifying the significant amount of GHG emissions associated with food transport can help countries mitigate climate change as part of a full accounting of emissions from their food system (Rosenzweig *et al.*, 2021). By understanding the interplay of energy-intensive processes across the food supply chain – such as in post-harvest management, transport, refrigeration and retail – countries can begin to look across their food systems to unlock novel mitigation opportunities. For example, consolidating and streamlining operations across the supply chain, through improved coordination of food supply chain actors, could greatly increase food transport efficiency (Wakeland *et al.,* 2012). Educational campaigns to promote best practices during harvesting and in post-harvest management could reduce the amount of food that is lost during transport, which would in turn improve transport efficiency and therefore reduce GHG emissions (FAO, 2004; Ippolito and Nigro, 2000). In a similar vein, developing climate-smart cold chain infrastructure could also reduce food loss and waste at various stages of the food supply chain, such as in transport, which could ultimately decrease the amount of land and GHG emissions used to produce food (Kummu *et al.,* 2012). In order to realize the potential climate benefits of a food systems approach, however, reliable data sources on historic and current food transport emissions must first be developed, as part of a full accounting on GHG emissions across the global food system.

3 Domestic food transport methodology overview

3.1 Overview

GHG emissions from food transport consist of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emitted from the combustion and evaporation of fuel for all domestic food transport activity, including domestic aviation, road transportation, railways, domestic water-borne navigation, and other transportation. The data presented in this methodology are taken as a fraction of total domestic transportation emissions, defined by IPCC category 1A3 (IPCC, 2019, Vol. 2) and reported by the PRIMAP-hist Third Party Reported dataset (Gütschow *et al.*, 2021 v2.2). Since domestic transportation emissions are responsible for 97.5 percent of global food transport emissions, these data are the focus of this methodology (Crippa *et al.*, 2021b).

3.2 Estimating the share of transportation attributable to food transport

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

$Emissions = (F_i / T_i) * E_i$

where:

Emissions = Gigagrams CO_2 equivalent (Gg CO_2e yr^{-1})

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

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

or

Million tonnes of oil equivalent 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 tonnes of oil equivalents yr^{-1} (Mtoe yr^{-1})

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

Gigagrams CO_2 equivalent yr^{-1} (Gg CO_2e yr^{-1})

4 Activity data for the United States of America, China and the European Union

Activity data for the United States of America, China and the European Union are estimated from three sources that contain specific information on the energy used in food distribution in those economies. 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.

4.1 United States of America

Activity data for the United States of America is estimated from the United States Department of Agriculture (USDA) report *The Role of Fossil Fuels in the U.S. Food System and the American Diet*, which contains data on the total amount of energy used in food transport in 2012 (USDA, 2017).

$F_{\text{U.S.}}$: 0.8 qBTU yr^{-1} = 20.2 Mtoe yr^{-1}

This was compared to the total transport estimates found in the U.S. Energy Information Administration's monthly energy review (EIA, 2020).

$T_{\text{U.S}}$: 26.1 qBTU yr^{-1} = 657.7 Mtoe yr^{-1}

4.2 China

Activity data for energy used in food transport in China is taken from Song *et al.* (2019), which approximates that total food system energy consumption was 7 573 petajoules (PJ) in 2012, which is equivalent to approximately 180 Mtoe (IEA, 2016). Furthermore, food transport amounted to 6 percent of total food energy consumption in that year. Therefore:

F_{China}: 10.8 Mtoe yr^{-1}

The total energy consumed in transport, found in the International Energy Agency (IEA) Energy Balances for China in 2012 (IEA, 2015) was:

T_{China}: 238.5 Mtoe yr^{-1}

4.3 European Union

For the European Union (EU), the share of transport emissions used for food is taken from the energy embedded in food consumed in the EU27 in 2013 (283 Mtoe) multiplied by the percentage of food-related energy used in food logistics (9.4 percent), multiplied by the share of transport in logistics (88 percent) (Monforti-Ferrario *et al.*, 2015).

$F_{E.U.}$: 23.4 Mtoe yr^{-1}

This figure was compared against IEA data for EU total energy consumption in transport (IEA 2015).

$T_{E.U.}$: 305.0 Mtoe yr^{-1}

4.4 Summary table

To summarize, activity data to estimate the food share of all transport is presented in the following table:

Table 1. Food share of domestic transport

Region	Food Transport (F_i) (Mtoe)	Total Transport (C_i) (Mtoe)	Food share (F_i)/(C_i) (percent)
United States of America	20.2	657.7	3.1
China	10.8	238.5	4.5
EU27	23.4	305.0	7.7

Source: Authors' own elaboration, based on USDA (2017), EIA (2020), Song *et al.* (2019), IEA (2015) and Monforti-Ferrario *et al.* (2015).

4.5 Food transport share of total domestic transportation emissions

Emissions from food transport in the United States of America, China, and the European Union can then be applied as a fraction of total domestic transport emissions in the 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.

5 Food transport emissions for other countries

As previously mentioned, domestic transportation emissions from the United States of America, China, and the EU represent 50.4 percent of global domestic transportation emissions. Unfortunately, specific data regarding food transport as a fraction of overall transportation is less readily available from other economies.

5.1 Food transport share of total domestic transportation emissions

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), 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 United States of America, China and the EU, given the magnitude of the emissions generated in those economies.

It is nevertheless useful to rely on the EDGAR-FOOD dataset to generate rough estimates of the country-level emissions from food transport, as there is generally a paucity of administrative data and country-specific studies on food transport beyond the aforementioned economies. Utilizing and improving the dataset can yield immediate results and help countries develop a more precise understanding of the magnitude of their national emissions that arise from food transport.

5.2 Methodology for extending emissions time series data

The EDGAR-FOOD data on food transport emissions does not extend beyond 2015 (Crippa *et al.*, 2021b). However, food transport emissions 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.

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). As 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 equivalent (Gg CO_2e yr^{-1}),

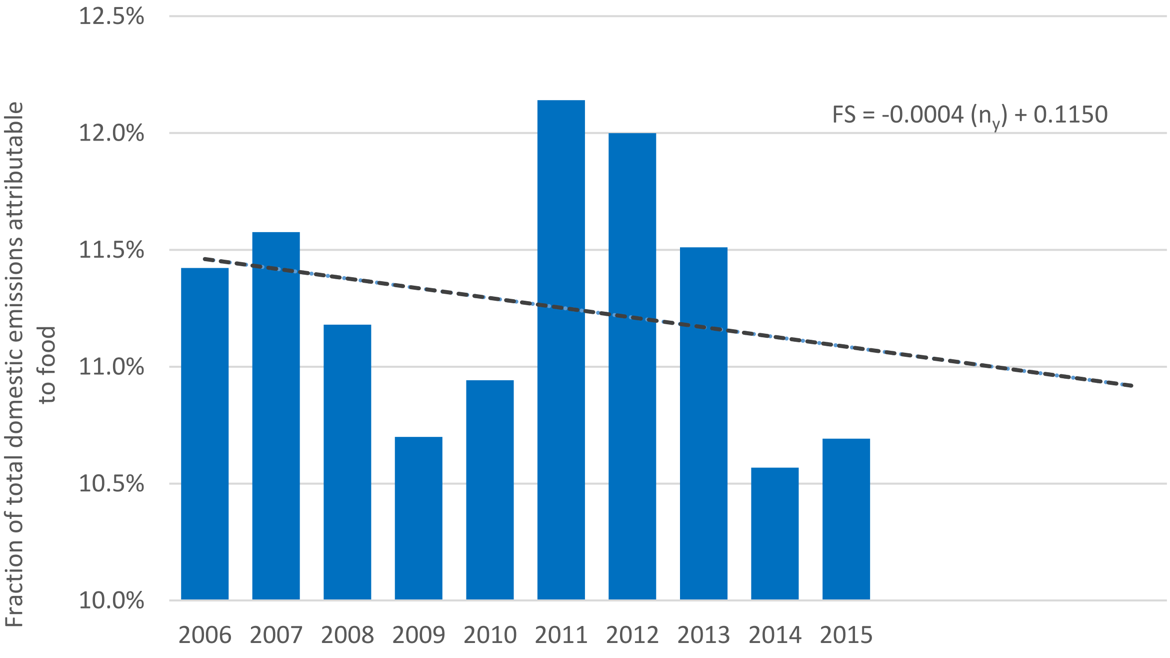
FS = estimated fraction of total domestic transport emissions attributable to food (i.e. food share) in country or region*, i*, in the inventory year, *y*,[1]

TTE = domestic food transport emissions in select country, *i,* for select inventory year, *y*, Gg CO_2e yr^{-1}.[2]

5.3 Example country

By using a randomly selected country, in this case Argentina, it is possible to demonstrate this methodology according to the previously outlined steps.

Figure 1. Food share of domestic transportation emissions in argentina, trendline (2006–2015)



Sources: Authors' own elaboration based on Gütschow *et al*. (2021 v2.2) and Crippa *et al.* (2021b).

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[1] Based on Crippa *et al*., 2021b and Gütschow *et al*., 2021

[2] From Gütschow *et al*., 2021

Figure 1 displays the food share for 2006–2015, calculated by dividing food transport emissions found in EDGAR-FOOD over total transport emissions from the PRIMAP-hist dataset.

For example: $FS_{ARG,2006}$ = (6 156.71 Gg CO_2eq / 53 900 Gg CO_2eq) = 0.1142.

For the years 2016–2019, the equation derived from a simple linear regression can be used to estimate the food share in years not covered by the EDGAR-FOOD dataset.

In this example, the country-specific trendline is expressed by the equation:

$FS_{ARG,y} = -0.0004(n_y) + 0.1150$

where

n_y = the number of years from the beginning of the time series, *n,* for inventory year, *y.*

Therefore: $FS_{ARG,2016} = -0.0004(11) + 0.1150 = 0.1106$.

Using the emissions formula from section 4.2, we can estimate food transport emissions in Argentina in 2016, as follows:

$FS_{ARG,2016} = 0.1106$

and

$TTE_{ARG,2016}$ = 63600 Gg CO_2eq

Therefore:

$Emissions_{ARG,2016}$ = 0.1106 * 63 600 Gg CO_2eq = 7 034.16 Gg CO_2eq

5.4 Notes on extending available data

This methodology can also be applied also in the reverse direction, i.e. using food shares calculated between 1990–1999 to estimate the pre-1990 food shares that can be applied to the PRIMAP-hist dataset. While this methodology may be useful for projecting the food share forwards and backwards, it becomes less reliable the further away the projection is from the available data.

6 Limitations and areas for advancement

6.1 Limitations

It is not sufficient to rely indefinitely on EDGAR-FOOD transport emissions data – which generally splits the world into “industrialized” and “developing” countries, and uses a rough global average for each group – given the vast inter-country diversity in food systems, transportation systems, geography, and income levels, among other factors. In particular, the authors of this work intend to develop and refine a more sophisticated model to estimate country-level food transport emissions going forward (see subsection 6.2). In the meantime, this methodology may provide useful estimates that can help countries begin to quantify emissions across their food supply chain and enable more nuanced approaches in the effort to advance climate-smart food systems.

The drawbacks of the methodology provided herein reflect the paucity of data available on this particular component of food system emissions. Still, it is useful to provide more detailed insight on the domestic food transport emissions of economies which represent over 50 percent of the global share of transport emissions (United States of America, China and the EU), while still providing less precise, but still country-specific, estimates for all other countries.

GHG emissions from international marine shipping of food are not included in this methodology, although that contributes only less than 5 percent of the total carbon footprint of global food transport (Crippa *et al*., 2021a). While large amounts of food products are shipped internationally, the GHG emissions of water transport, in kg CO_2eq per tonne-kilometre, are 3–5 percent of the level of emissions associated with road transport, and 0.1–1.8 percent of air transport (Ritchie and Roser, 2020). Still, incorporating GHG emissions from international shipping in the accounting of the carbon footprint of food distribution is needed in order to determine the true material footprint of food consumption and production of different countries.

6.2 Areas for advancement

Work towards estimating the carbon footprint of food transport at the country level can be advanced in several ways. The present approach could be expanded on by including other country- and region-specific studies that estimate the amount of fuel consumed in domestic food transport, or the distance travelled annually by food-distributing vehicles.

Other data sources could help explain and estimate variations in food distribution between countries, such as: GDP per capita, urbanization levels, proxies for transportation infrastructure development (such as rail line density), and geographic considerations such as the distance from major ports and food distribution centres to cities, among other factors. Analysis linking the geography of food production to the geography of food consumption could estimate distances that different food products travel both internationally and domestically, as well as the concomitant emissions associated with that distribution.

The evolving role of refrigeration in food transport, and the fact that emissions from temperature-controlled transport are likely to rise in the coming decades due to increases in ambient air temperature as a result of climate change (James and James, 2010). As the energy demands of refrigerated food transport systems change over time, it will alter the amount of total domestic transportation emissions that are attributable to food distribution. Therefore, future work on the impact of food transport on climate change should also incorporate the projected impacts of climate change on food transport.

7 Notes

7.1 Global warming potential used

The emissions data can be converted from methane and nitrous oxide to CO_2 equivalents using three different global warming potentials as found in the IPCC Second Assessment Report (SAR), Fourth Assessment Report (AR4), and Fifth Assessment Report (AR5). The PRIMAP-hist dataset uses AR4 CO_2 equivalents, and Crippa *et al*. use AR5 CO_2 equivalents as shown below.

CO_2eq (AR4)

For CO_2eq (AR4) calculations, GWP-CH_4 = 25 (100-year time horizon global warming potential), to convert Gg CH_4 to Gg CO_2eq. GWP-N_2O = 296 to convert Gg N_2O to Gg CO_2eq (IPCC, 2007).

CO_2eq (AR5)

For CO_2eq (AR5) calculations, GWP-CH_4 = 28 (100-year time horizon global warming potential), to convert Gg CH_4 to Gg CO_2eq. GWP-N_2O = 265 to convert Gg N_2O to Gg CO_2eq (IPCC, 2014).

7.2 Uncertainties

Uncertainties in estimates of GHG emissions are due to uncertainties in emission factors and activity data. They may be related to, inter alia, natural variability, partitioning fractions, lack of spatial or temporal coverage, spatial aggregation, or modelling errors. More detailed information on uncertainties associated with applying the IPCC Guidelines can be found in the IPCC report *Good practice guidance and uncertainty management in national greenhouse gas inventories* (IPCC, 2006). In the case of transportation, more detailed information is available in the IPCC Guidelines (IPCC, 2019: Vol.2).

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