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Developing an Air Pollutant Emissions Database for Global Economic Analysis

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According to the Global Burden of Disease study (Cohen et al., 2017), in 2015 ambient air pollutant emissions caused 4.2 million deaths and a loss of 103.1 million disability-adjusted life-years, making it the fifth-ranked global risk factor. In terms of the welfare costs of mortality and illnesses associated with outdoor air pollutant emissions, global estimates for 2015 range between $2.7-3.2 trillion (Coady et al., 2015; OECD, 2016). Still, while greenhouse gas emissions are usually well represented in many global economic databases and models, air pollutant emission accounts in most cases are not included. In particular, this is the case for the widely used Global Trade Analysis Project (GTAP) Data Base and model. In this paper we describe the methodology used to produce a global air pollutant emissions dataset consistent with the GTAP Data Base version 10A. In addition to the non-land use sources, emissions from land use activities are estimated by land cover type, based on the volume of burned biomass and emission factors. The emissions database can be readily incorporated in GTAP-based computable general equilibrium models, enabling assessments of a wide range of policy questions, including the health co-benefits from climate mitigation policies. We illustrate an application of the air pollutant emissions database by tracking changes in primary PM2.5 emissions embodied in trade between 2004 and 2014.

JEL codes: C61, D57, D58, Q54, Q56.

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1. Introduction

In recent years, a number of studies have contributed to the assessment of air pollutant emissions-related externalities at the regional and global scales. According to the Global Burden of Disease study (Cohen et al., 2017), in 2015 ambient air pollutant emissions caused 4.2 million deaths and a loss of 103.1 million disability-adjusted life-years, making it the fifth-ranked global risk factor. In terms of the welfare costs of mortality and illnesses associated with outdoor air pollutant emissions, global estimates range between $2.7-3.2 trillion for 2015

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(Coady et al., 2015; OECD, 2016). This is equivalent to 40% of global expenditures on health and is 10 times higher than global investment in renewable energy (World Bank, 2017; FS-UNEP/BNEF, 2017).

With such a high magnitude of air pollutant emissions-related externalities, implementing more stringent environmental policies (e.g. emissions taxation or elimination of energy subsidies) may result in significant co-benefits from reduced mortality and morbidity, as well as increased labor productivity (Saari et al., 2015; Vandyck et al., 2018; Markandya et al., 2018; Chen et al., 2020). While CO_2 and non-CO_2 greenhouse gas (GHG) emissions are usually well represented in many global economic databases and models, air pollutant emission accounts in many cases are not included. One of the reasons behind this situation is that unlike carbon budget estimates from changes in GHG emissions, health impacts from changes in air pollutant emissions have to be accessed using specialized modelling tools and techniques (e.g. Van Dingenen et al., 2018; IIASA, 2017).

In several applications, a direct link between multi-regional input-output (MRIO) model accounts and air pollutant emission flows has been used to explore the interactions between trade, air pollutant emissions and final consumption (e.g. Li and Liu, 2020; Meng et al., 2019; Yasmen et al., 2019; Zhang et al., 2017; Kanemoto et al., 2014). Various approaches and data sources have been used in the literature to incorporate air pollutant emission accounts in the MRIO framework, reporting different gases, sectors and regions. These include EXIOBASE (Stadler et al., 2018), Eora (Lenzen et al., 2013) and WIOD (Timmer et al., 2015).

The purpose of this paper is to describe the methodology used to produce an air pollutant emissions dataset consistent with the Global Trade Analysis Project (GTAP) Data Base (Hertel, 1997), one of the most widely used databases for global economic analyses (van Tongeren et al., 2017). The air pollutant emissions dataset constructed in the paper is consistent with the GTAP Data Base version 10A (Aguiar et al., 2019), which reports data for four benchmark years: 2004, 2007, 2011 and 2014. This effort complements the GTAP non-CO_2 greenhouse gas (GHG) emissions database (Chepeliev, 2020a) and CO_2 emissions data, integrated in the standard GTAP Data Base (Aguiar et al., 2019).

We construct the emissions database for 9 pollutants, all 141 GTAP regions and for the four benchmark years. Emissions are linked to economic activities and three sets of emission sources: consumption (by intermediate and final users), endowment use (land and capital) and output. As a main data source this study uses the EDGAR Version 5.0 database (Crippa et al., 2020). To assist with emissions allocation between consumption-based sources, the IIASA GAINS-based model emission factors are used (Coady et al., 2015). In addition, emissions from land use activities (biomass burning) are estimated by land cover type, based on the volume of burned biomass (FAO, 2020) and emission factors. These emissions are reported separately without association to emission drivers. We illustrate an application of the air pollutant emissions database by tracking changes in primary PM2.5 (particles less than 2.5 micrometers in aerodynamic diameter) embodied in trade between 2004 and 2014.

Preceding this effort, several other studies have linked air pollutant emissions to the GTAP Data Base and GTAP-based computable general equilibrium (CGE) models. These include Meng et al. (2019), OECD (2016) and Nam K.-M., et al. (2014). At the same time, the current effort has several advantages over existing literature. First, the air pollutant emissions database developed in this study is consistent with the latest version the GTAP Data Base – version 10A, while datasets discussed in the existing literature were developed for GTAP version 9 or earlier. Second, the emissions database developed in this paper is made publicly available to all GTAP Data Base subscribers, making it open to the wide modelling community. Third, the current approach covers 9 air pollutants – exceeding most of the previously implemented efforts. Fourth, both land use-based and non-land use emissions are reported in the database, providing a complete coverage of the air pollutant emission sources (most previous efforts report emissions from non-land use activities only). Fifth, being largely based on the widely used EDGAR emissions database (Crippa et al., 2020), the air pollutant emission accounts can be readily linked to the existing global atmospheric source-receptor models that also rely on EDGAR as the source of their emissions data, such as TM5-FASST (Van Dingenen et al., 2018). The latter allows for a consistent assessment of the impacts of energy and environmental policies (as implemented in the CGE model) on human health, agricultural crop production and short-lived pollutant climate metrics. Some previous efforts (e.g., Meng et al., 2019) are based on the data sources not accompanied by the global atmospheric source-receptor models (Huang et al., 2014). Finally, we believe that the current contribution provides a more consistent mapping of emission accounts to the GTAP Data Base, compared to previous efforts, benefiting from the structure of the EDGAR air pollutant emission accounts. These specific advantages of the GTAP air pollutant emissions database are discussed in more detail in the paper.

The rest of the paper is organized as follows. Section 2 gives an overview of the available air pollutant emissions data sources and provides justification of the selected data inputs. Section 3 discusses an overall approach to the construction of the GTAP-consistent air pollutant emission accounts, as well as provides estimates of the land use (biomass burning) emissions. Section 4 provides an overview of the final database. Section 5 showcases a numerical illustration of the air pollutant emissions database by tracking changes in primary PM2.5 emissions embodied in international trade. Finally, Section 6 concludes.

2. Air pollutant emissions data sources and pre-processing

Several sources for the global air pollutant emissions data are available, which can be used for the construction of GTAP-consistent emission accounts either separately or combined. In our effort to construct the air pollutant emission accounts consistent with the GTAP Data Base, we impose several criteria on the source data. First, we are aiming for a global dataset with (at least) country-level coverage. Second, the underlying emissions dataset should be based on a standardized methodology and with regular updates, to support future releases of the GTAP Data Base. Third, the database should distinguish sources of air pollutant emissions, which can be further linked to economic activities, as presented in the GTAP Data Base.

Considering the aforementioned criteria, in this paper we are relying on the EDGAR Version 5.0 database as a main source of air pollutant emissions (Crippa et al., 2020). The EDGAR database provides air pollutant emissions linked to 38 emission sources (Appendix A) and 229 countries[1] (Crippa et al., 2020), covering the period 1970-2015. Emissions for nine pollutants are reported in the database: black carbon (BC), carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), organic carbon (OC), particulate matter 10 (PM10), particulate matter 2.5 (PM2.5) and sulfur dioxide (SO_2).[2] For estimates of the underlying energy volumes, both EDGAR and GTAP rely on the extended energy balances developed by the International Energy Agency (IEA) (Crippa et al., 2020; McDougall and Chepeliev, 2021).

The disaggregated data in the EDGAR database lends itself to a detailed mapping to the GTAP Data Base sectors and corresponding sources (e.g. intermediate inputs, output, endowments, etc.), as will be discussed in Section 3.

Several other data sources were also considered as an alternative or addition in the preparation of air pollutant emissions dataset. The GAINS model (IIASA, 2017) provides emissions accounting for five substances (NH_3, NO_x, PM, SO_2 and VOCs) classified by sector and fuels/activities. Data is provided by regions/countries in 5-year time steps, starting from 2005. While this dataset has global coverage and, in some cases, enables more accurate mapping to the GTAP Data Base's sectors compared to EDGAR, the higher disaggregation of emission sources cannot be

[1] EDGAR also reports emissions for two additional categories, which are not distributed by countries/regions: international shipping and international aviation. Treatment of these two categories is discussed below.

[2] The list of pollutants in EDGAR v5.0 has changed from the previous versions. In particular, in EDGAR v4.3.2 (Crippa et al., 2018) PM2.5 emissions were split into fossil and bio flows, while in EDGAR v4.3.1 (Crippa et al., 2016) NMVOC emissions were split into short and long cycle carbon.

fully utilized due to the differences in GTAP and GAINS sectoral classifications. Furthermore, data reported in GAINS are represented in 5-year time steps that do not match the GTAP 10 Data Base reference years. Compared to EDGAR, GAINS also reports for a lower number of air pollutants.

GAINS data, however, can be used to improve the allocation of the EDGAR-sourced emissions between corresponding drivers and sources. As discussed in the next section, we use GAINS-based emission factors to provide a more accurate mapping of selected air pollutants (SO_2, NO_x and PM2.5) to the corresponding fossil fuel uses in the GTAP Data Base.

Another source of air pollutant emissions data is available from the United Nations Food and Agriculture Organization (FAO), covering emissions from agricultural-related activities (FAO, 2017). But, unlike the GHG emissions, which are covered in detail by FAOSTAT (Chepeliev, 2020a), air pollutant emissions data are reported only in the form of ammonia (NH_3) emissions from agriculture. Since EDGAR v5.0 does not report emissions from large scale biomass burning and activities of land use, land-use change and forestry (Crippa et al., 2020), we use FAO-reported volumes of biomass burning by land cover type and emission factors to estimate emissions from land use activities, as discussed in Section 3.

A database on greenhouse gas emission factors (IPCC-EFDB), developed by the Intergovernmental Panel on Climate Change (IPCC, 2017), provides detailed information on emission factors for different technologies, fuels and air pollutants. The IPCC database does not provide emission levels by country, but only country-generic emission factors. This information is used to assist with EDGAR-based emissions redistribution between drivers and sources. A corresponding approach is discussed in more detail in the next section.

Global air pollutant emission inventories developed by Peking University (PKU) provide a dataset that is largely comparable to EDGAR (Huang et al., 2014).[3] The PKU database covers the period 1960-2014 and reports emissions of ten types of air pollutants at a spatial resolution of 0.1^{o} x 0.1^{o} for 223 countries. This database however does not cover NMVOC emissions, as well as it does not report some non-combustion emission sources (e.g. fugitive emissions, manure management, rice cultivation, direct soil emissions, etc.). One specific feature of the PKU dataset, which makes it somewhat less useful than EDGAR, is the much lower sectoral resolution of reported emissions. PKU distinguishes five sectors—energy production, industry, residential/commercial, agriculture and transportation, while EDGAR v5.0 reports emissions at a much more disaggregate sectoral level (e.g. distinguishing aviation, navigation, road transportation, rail transportation and other transportation within a single transportation sector reported by PKU). This feature of EDGAR enables a more transparent mapping to the GTAP sectors.

[3] The most recent PKU emission accounts are available at http://inventory.pku.edu.cn/data/data.html.

Another advantage of EDGAR over PKU, is that due to the wider use of the former dataset, several global atmospheric source-receptor models, such as TM5-FASST (Van Dingenen et al., 2018), have been developed based on EDGAR. This feature facilitates linking GTAP-based CGE models (with EDGAR-based emission accounting) and some of the existing atmospheric source-receptor models.

For additional discussion and comparison of the available global air pollutant emission databases interested readers are referred to Hoesly et al. (2018) and Huang et al. (2014).

3. Air pollutant emissions data mapping to the GTAP Data Base

This section provides a description of the approach used to link the EDGAR-based air pollutant emissions data with the GTAP 10A Data Base. In this effort, in line with Irfanoglu and van der Mensbrugghe (2015) and Chepeliev (2020), we associate each pollution flow with one of the four sets of emission sources: output by industry, endowment by industry, input use by industry and input use by households. To provide a more accurate allocation of emissions between different types of fossil fuel consumption by industry and households we use the GAINS-based emission factors, reported in Coady et al. (2015), IPCC-sourced emission factors provided in IPCC (2017), as well as BC and OC emission factors based on multiple data sources (Kupiainen and Klimont, 2007; Chow et al., 2011; EEA, 2019). Figure 1 provides an overview of the database construction process.

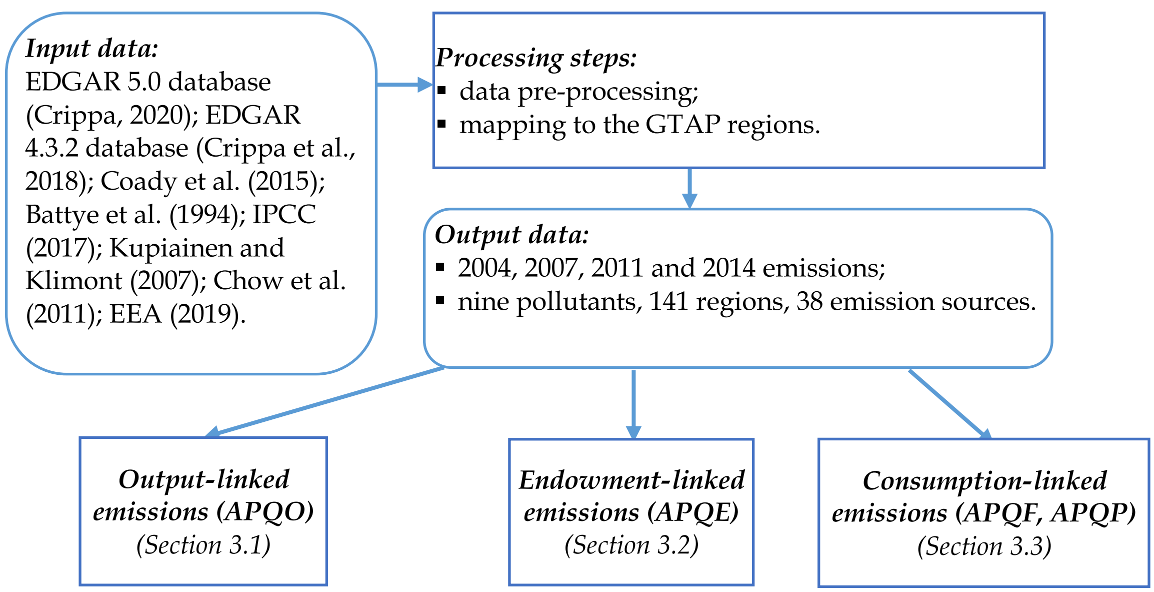

Figure 1. GTAP air pollutant emissions database construction process.

Notes: This figure excludes treatment of the land use emissions (discussed in section 3.4).

Source: Author calculations.

The EDGAR v4.3.2 database reports PM2.5 emissions from fossil fuel (PM2.5f) and bio (PM2.5b) sources (Crippa et al., 2018).4 We use this distinction to provide a more consistent mapping of the PM2.5 emissions reported in the EDGAR v5.0 to the GTAP emission drivers. As the GTAP energy database (McDougall and Chepeliev, 2021) does not report energy flows for biomass or biofuels use, we apply different mappings for PM2.5f and PM2.5b flows. These are reported in Appendixes B and C, respectively. PM2.5 emissions from the EDGAR v5.0 are first split into bio and fossil parts, using country and IPCC category-specific shares from the EDGAR v4.3.2. They are then mapped to the emission drivers, following an approach discussed in sections 3.1-3.3 and aggregated to a single PM2.5 category in the final database.

3.1. Air pollutant emissions associated with output by industries

In the case of output-driven categories, emissions are redistributed between corresponding emitting sectors proportionally to the value of sectoral output (Appendixes B and C). With the defined mapping between IPCC categories and the GTAP emission sources, as well as mapping between the IPCC categories and the GTAP emission drivers, output-associated emissions (*APQO*) are estimated according to the following formula:

$$APQO_{t,e,k,r} = \sum_{c \in \left\{ \substack{SecMap(c,k,e) \\ and\ DriveMap(c,\text{"Output"},e)} \right\}} \frac{EmiReg_{t,e,c,r} ValRedist_{c,e} ValOutpt_{t,k,r}}{\sum_{i \in \{SecMap(c,i,e)\}} ValRedist_{c,e} ValOutpt_{t,i,r}},$$

where *t* is the set of years (2004, 2007, 2011 and 2014); *e* is the set of 9air pollutants; *k, i* represent the 65 GTAP sectors; *r* represents the set of 141 GTAP regions; *c* is the set of IPCC emission categories. *ValRedist* identifies cases with emissions redistributed proportionally to GTAP values[5] (such categories are indicated by "#" in Appendixes B and C). *SecMap* provides the mapping between IPCC categories and GTAP emission sources, while *DriveMap* provides the mapping between IPCC categories and GTAP emission drivers.[6] *EmiReg* represents EDGAR-sourced

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[4] Split into bio and fossil-fuel parts in the EDGAR v4.3.2 database is provided for the PM2.5 emissions only and is not available for other substances.

[5] We divide all IPCC categories into IPCC categories: (a) emissions redistributed proportionally to GTAP values (value of output, endowment or consumption); and (b) those with emissions redistributed based on energy data use and/or emission factors. The second treatment is applied to all pollutants except PM2.5_bio. In the latter case all emissions are redistributed proportionally to value flows. For instance, in the case of "3B" category (Solvent and other product use: degrease), country-specific emissions are distributed proportionally to the value of chemicals ("chm") intermediate use by five sectors - "i_s", "nfm", "fmp", "ele" and "ros" (as specified in the Appendix B).

[6] These mappings (*SecMap* and *DriveMap*) are generic for all air pollutants.

emissions in gigagrams (Gg)[7] and *ValOutpt* provides value of output in million USD.

An example of the emissions associated with output includes emissions from the production of pulp, paper, food and drink. These emissions are redistributed proportionally to the values of output of the ten GTAP sectors that represent corresponding activities and are listed in the Appendix B.

3.2. Air pollutant emissions associated with endowment by industries

Endowment sources account for the smallest share of pollution in all cases. All endowment-driven IPCC pollution categories are redistributed between drivers and sectors proportionally to the GTAP value flows (Appendix B), which is similar to the output-driven pollution treatment:

$$APQE_{t,e,m,k,r} = \sum_{c \in \left\{ \substack{SecMap(c,k,e) \\ and\ DriveMap(c,m,e)} \right\}} \frac{EmiReg_{t,e,c,r} ValRedist_{c,e} Costs_{t,m,k,r}}{\sum_{i \in \{SecMap(c,i,e)\}, j \in \{DriveMap(c,j,e)\}} ValRedist_{c,e} Costs_{t,j,i,r}},$$

where *m, j* are defined over the set of endowment drivers (land and capital), used for emissions reallocation; *Costs* coefficient represents the cost structure in million USD.[8]

In the database there are two cases of the endowment-linked emissions. The first instance includes emissions from the cultivation of rice, which are linked to the land endowment in the GTAP rice sector (Appendix B). The second case includes emissions from manure in pasture, land and paddock. In the latter case emissions are redistributed proportionally to the values of the capital endowment[9] in the three GTAP livestock and animal-related sectors – cattle, raw milk and other animal products (Appendix B).

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[7] 1 Gg equals 1000 metric tons.

[8] The cost structure is constructed as a combination of the cost structure of firms and cost structure of consumption, as reported in the "gsdview.har" file of the GTAP 10A Data Base (coefficients "NVFA" and "NVPA" respectively).

[9] In the GTAP Data Base value of animal stock (e.g. cattle) is captured via the capital input in the corresponding sector (e.g. bovine cattle, sheep, goats and horses).

3.3. Air pollutant emissions associated with consumption

3.3.1. Non-combustion emissions

Consumption-related pollution reallocation is treated in two ways. In the case of pollution linked to the consumption of chemical products the treatment is similar to the endowment- and output-driven pollution, both for firms (*APQF*) and households (*APQP*):

$$APQF_{t,e,k,j,r} = \sum_{c\in\left\{\substack{SecMap(c,j,e)\\ and\ DriveMap(c,k,e)}\right\}} \frac{EmiReg_{t,e,c,r} ValRedist_{c,e} Costs_{t,k,j,r}}{\sum_{s\in\{SecMap(c,s,e)\},i\in\{DriveMap(c,i,e)\}} ValRedist_{c,e} Costs_{t,i,s,r}},$$

where *k, i, j* represent the 65 GTAP sectors; *s* is the set of emission sources and includes traded commodities and households.

$$APQP_{t,e,k,r} = \sum_{c\in\left\{\substack{SecMap(c,"HHs",e)\\ and\ DriveMap(c,k,e)}\right\}} \frac{EmiReg_{t,e,c,r} ValRedist_{c,e} Costs_{t,k,"HHs",r}}{\sum_{s\in\{SecMap(c,s,e)\},i\in\{DriveMap(c,i,e)\}} ValRedist_{c,e} Costs_{t,i,s,r}},$$

where the *"HHs"* label identifies households.

An example of the non-combustion consumption-related emissions associated with both firms' and households' consumption includes emissions from the non-energy use of lubricants and waxes. In this case emissions are redistributed between all sectors and households proportionally to the value of the use of chemical products by these agents.

3.3.2. Fossil fuel combustion emissions: overall approach and energy flow estimates

A different treatment is applied to the IPCC categories associated with the fossil fuels' combustion (IPCC categories without "#" sign in the Appendix B). Figure 2 provides an overview of the general approach to the fuel combustion-related emission redistribution.

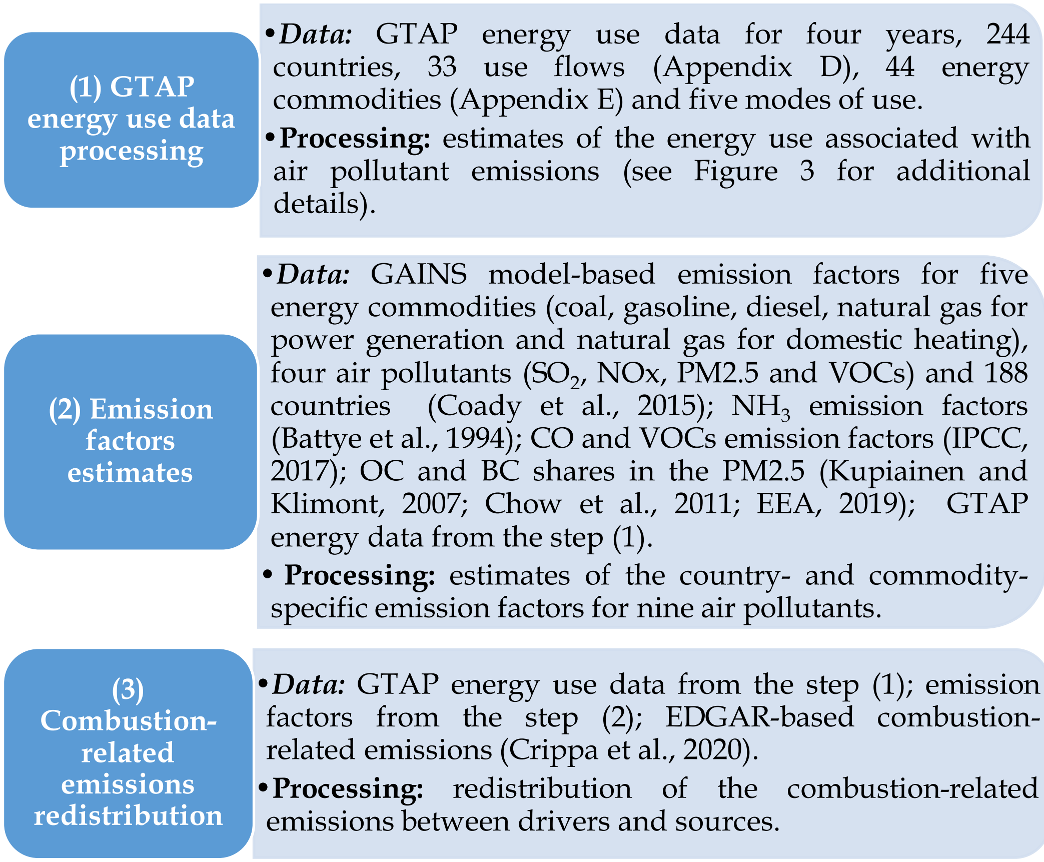

Figure 2. Steps to redistribute the fuel combustion-related emissions.

Source: Author calculations.

In the case of combustion-related emissions, in the first step, we estimate energy use associated with air pollutant emissions. In the case of some IPCC pollution categories, we assume that all energy use is associated with the corresponding pollution, while in other cases a share of all energy use is considered. We consider only such energy use that is associated with energy combustion and exclude fuel feedstocks that are transformed or exported, which, for instance, is the case for petroleum industry with high volumes of oil transformation. Figure 3 provides an overview of the energy data processing steps for the fuel combustion-related emissions treatment.

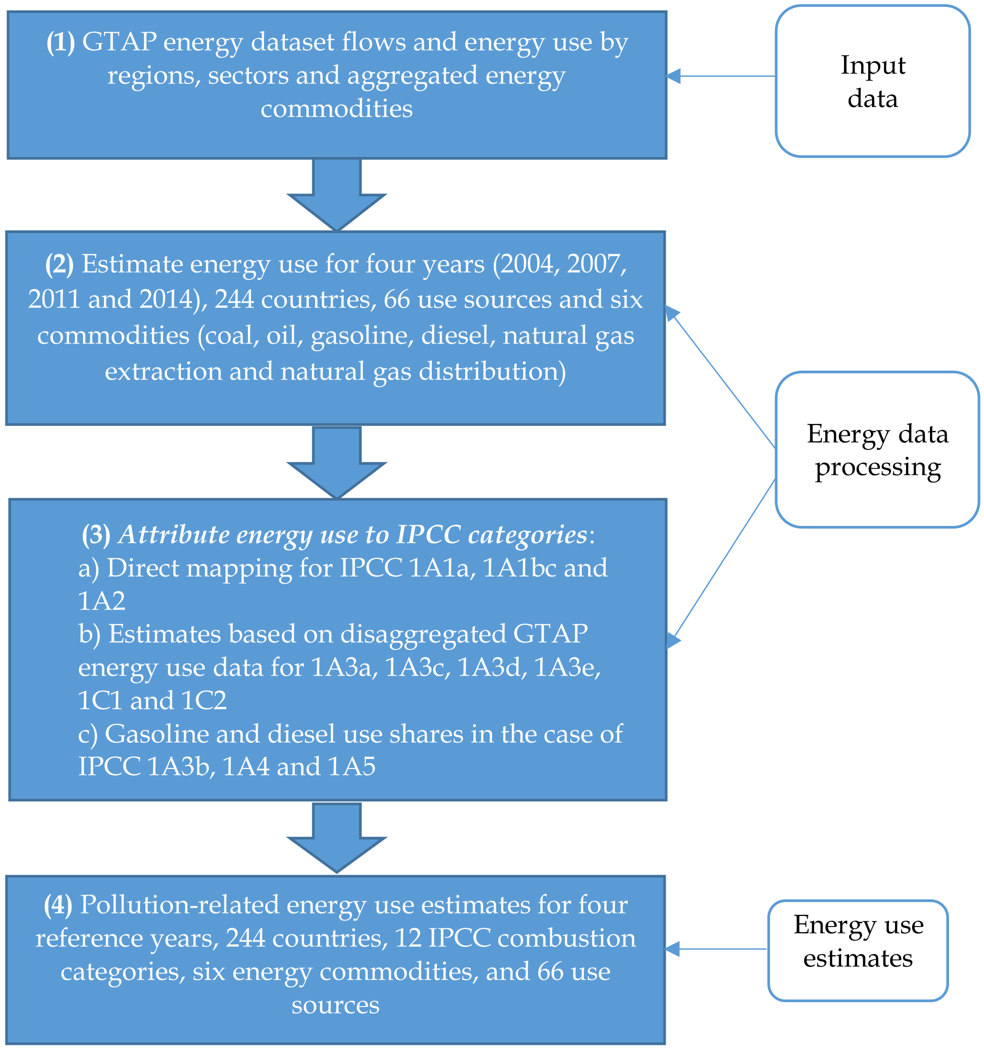

Figure 3. GTAP energy data processing for the fuel combustion-related emission estimates.

Source: Author calculations

The GTAP 10A Data Base energy data is not as disaggregated as required for the development of the air pollutant emissions database development, therefore we apply an additional disaggregation. This is the case for petroleum products, which are reported in aggregate in the GTAP 10A Data Base, while available emission factors are differentiated for gasoline and diesel. We also need energy use data at a country level (rather than by composite regions). To implement this, we use the GTAP 10A energy dataset (EDS) (McDougall and Chepeliev, 2021) with the corresponding flows reported in the GTAP 10A Data Base energy module (IEA, 2015a; 2015b). The EDS data provides energy use by years, countries, 33 use flows, 44 energy commodities and five modes of use. Using these two data sources we estimate energy use for four reference years (2004, 2007, 2011 and 2014), 244 countries, 66 use sources (65 GTAP 10A Data Base sectors and households) and six commodities (coal, oil, gasoline, diesel, natural gas extraction and natural gas distribution).

Using the mappings between IPCC emission sources, emission drivers and the GTAP use sources (Appendix B), we allocate estimated energy use flows to the IPCC categories. In the case of public electricity and heat production, other energy industries, as well as manufacturing industries and construction, we assume that the EDGAR-based emissions are redistributed based on all energy use volumes and one-to-many or one-to-one mapping from the IPCC codes to the GTAP use categories is applied. For instance, in the case of coal use in public electricity and heat production, we assume that the emissions are redistributed (in this case only between drivers, as the public electricity and heat production is mapped to a single GTAP sector) based on the coal use data.

In the case of transportation activities – domestic aviation, road transportation, rail transportation, inland navigation, other transportation, international aviation and international navigation – there is no available one-to-many or one-to-one mapping from the IPCC to GTAP use categories. For instance, GTAP's other transportation sector includes rail, road and other transportation IPCC categories (Appendix B). Similarly, air transportation includes both domestic and international aviation. To estimate energy use flows for such categories we use EDS data. A list of the corresponding IPCC categories and mapping to the EDS commodities are provided in the Appendix F.

Road transportation IPCC category is mapped to the other transportation activity and households (Appendix B). To provide a more consistent reallocation of the emission flows, we assume that all gasoline is associated with road transportation activities by households, however, not all diesel is used for road transportation. Therefore, we assume that in the case of households use, the share of diesel used for road transportation equals the share of diesel used for road transportation in total national diesel consumption. For instance, if country A consumes 100 tons of oil equivalent (toe) of diesel fuel of which 80 toe (or 80%) is consumed by road transportation, then we assume that in the case of households the share of diesel used for the road transportation equals 80%, while the remaining 20% is used for the other purposes (e.g. heating).

Finally, in the case of households under residential and other sectors category, we assume that no emissions are associated with gasoline use (as the gasoline-related emissions are attributed to road transportation activities). The share of diesel associated with emissions by households within this category equals "1" less the share of diesel associated with the road transportation use (this would be 0.2 in case of the example above). This step finalizes the GTAP energy data processing for combustion-related emission estimates (Figure 3).

3.3.3. Fossil fuel combustion emissions: estimates of emission factors and emissions redistribution

In general, energy use statistics alone could be enough to redistribute the air pollutants between drivers and sectors based on an assumption of uniform emission factors for different energy commodities and industrial processes. But, as the literature suggests (Coady et al., 2015; IPCC, 2017), this is not the case, as emission factors vary significantly across commodities and activities. We combine multiple data sources (Battye et al., 1994; Coady et al., 2015; IPCC, 2017; Kupiainen and Klimont, 2007; Chow et al., 2011; EEA, 2019) to derive country-, sector-, energy commodity- and pollutant-specific emission factors.

The International Monetary Fund (IMF) energy subsidies database (Coady et al., 2015) provides emission factors for 188 countries, five energy commodities (coal, gasoline, diesel, natural gas for power generation and natural gas for domestic heating) and four air pollutants (SO_2, NOx, PM2.5 and VOCs) based on the IIASA GAINS model. We first estimate weighted average emission factors for seven aggregate regions,[10] five energy commodities and four air pollutants to gap-fill the country cases with unavailable data. For each country with unavailable emission factors, we further use emission factors from the corresponding aggregate region. As the weights for the aggregate region-average emission factors, we use the energy data flows estimated in Step 1 (Figure 3). Emission factors for natural gas for domestic heating are applied to natural gas used by households. In the case of natural gas used by industrial users and commercial consumers we apply the emission factors for natural gas used in power generation.

We further map four air pollutants from Coady et al. (2015) to seven air pollutants reported in the EDGAR dataset. The corresponding mapping is provided in the Appendix G. In the case of the BC and OC emissions, we further adjust the PM2.5 emission factors based on the percentage shares of BC and OC in total PM2.5 mass. The corresponding BC and OC mass shares are estimated for six energy commodities (coal, oil, gasoline, diesel, natural gas extraction and natural gas distribution) and 66 emission sources based on Kupiainen and Klimont (2007), Chow et al. (2011) and EEA (2019).

In the case of emission factors for ammonia (NH_3), we use data from Battye et al. (1994) and assume that these factors are uniform across countries. For the conversion of emission factors to uniform units (kt/PJ) we use data on the density of the corresponding fuels (JRC, 2007; Unitrove, 2017). The energy content of fuels is sourced from NER (2017). In the case of natural gas, we use the emission factors

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[10] The corresponding aggregate regions include East Asia and Pacific, Europe and Central Asia, Latin America and the Caribbean, Middle East and North Africa, North America, South America and Sub-Saharan Africa. The country mapping for each region is available at https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

for utility and industrial boilers for all sectors except for households; for residential users we apply the emission factors of commercial boilers (Battye et al., 1994).

To derive the CO emission factors, we use the IPCC (2017) database. In the IPCC database, emission factors for combustion activities are provided for the 14 IPCC categories (Appendix H). Out of the 14 IPCC categories, only eight have available emission factors for CO, which we map to the GTAP use categories (Appendix H). In some cases, the IPCC database reports identical emission factors for several IPCC categories (e.g. 1A4A, 1A4B, 1A4C1).

In terms of the emission drivers, out of the 23 fuels reported in the IPCC emission factors database for CO, only 10 have non-zero values and we map them to the six energy commodities for further emissions redistribution (Appendix I). IPCC-based estimation of the CO emission factors finalizes the Step 2 of the emissions redistribution process (Figure 3). As Coady et al. (2015) do not provide VOCs emission factors for natural gas and coal combustion, we use the IPCC values to gap fill this dataset.

We do not map emission factors related to the biomass combustion, as in the GTAP energy dataset all energy flows associated with the biomass or biofuel use are discarded from the construction process (McDougall and Chepeliev, 2021). We use corresponding value flows to redistribute the PM2.5 bio emissions (Appendix C). Once available within the GTAP Data Base accounting framework, a reliance on the biomass energy flows could improve the treatment of the PM2.5 bio emissions redistribution. However, it should be noted that in the case of the key emissions category – residential and other sectors, which accounts for over 64% of the global PM2.5 bio emissions – emission flows are associated with a single agent – households (Appendix C), which implies a direct mapping and thus no weighted flows-based redistribution is applied in this case.

To assist with the combustion-related emissions allocation, we estimate emission weights multiplying combustion-related energy use by the corresponding emission factors to derive the *EFEmiReg* values. With the processed energy use data and estimated emission factors, we move to the Step 3 (Figure 3) and redistribute combustion-related emissions (*ENCOMBEMI*):

$$ENCOMBEMI_{t,r,b,f,s,e} = \frac{EmiReg_{t,e,b,r} EFEmiReg_{t,r,b,f,s,e}}{\sum_{q,v} EFEmiReg_{t,r,b,q,v,e}},$$

where b is the set of air pollutant emission categories in the IPCC emission factors database associated with fossil fuel combustion (Appendix H); f, q represent the set of six energy commodities (coal, oil, gasoline, diesel, natural gas extraction and natural gas distribution) associated with air pollutant emissions; s, v correspond to emission sources.

An example of the combustion-related emissions includes emissions from the other energy industries (excluding electricity and heat production). In the GTAP

Data Base, the corresponding set of industries is represented by five sectors – mining of coal, oil and gas, production of petroleum products and distribution of gas (Appendix B). The EDGAR-sourced emissions for this category are redistributed between the corresponding five GTAP sectors and four fossil fuel commodities (coal, oil, gas and petroleum products) based on the sector and commodity-specific emission weights, as discussed above.

International aviation and navigation emissions are redistributed between countries based on the value of exports reported in GTAP 10A Data Base for air transport and water transport respectively, excluding exports of travelers' expenditures. These emissions are further mapped to drivers and users and added to the consumption-related emissions. Under such treatment, for example, air pollutant emissions associated with a ship leaving from Rotterdam is accounted in the country of the ship's destination.

After this step, we have redistributed over 99.9% of emissions reported in the EDGAR database. However, as was identified, there are some cases (less than 0.1% of the global air pollutant emissions) where EDGAR-reported emissions corresponding to the combustion-related drivers and users in the GTAP Data Base, have no energy consumption. To deal with such cases, we map such instances to users with non-zero energy consumption. Appendix J provides the mapping.

Finally, the redistributed emissions from the fossil fuel combustion (*ENCOMBEMI*) are mapped to the emissions associated with the consumption by households (*APQP*) and firms (*APQF*).

3.4. Land use emissions

EDGAR v5.0 does not report emissions from large scale biomass burning and activities of land use, land-use change and forestry (Crippa et al., 2020). To complement the are pollutant database with these emissions, we use the FAO-reported volumes of biomass burning by land cover type and emission factors compiled from several sources. Figure K.1 (Appendix K) provides an overview of the biomass burned (dry matter) by land cover types (FAO, 2020). Volumes of the burned biomass declined between 2004 and 2011, but increased in 2014, reaching 1,704 million tons. In 2014, organic soils accounted for around 41% of the total volume of biomass burned followed by other forests (31%) and humid tropical forests (28%).

Table K.1 (Appendix K) provides a summary of assumptions regarding the value of emission factors by land cover type. These emission factors are primarily based on Akagi et al. (2011) and are complemented by estimates from Yokelson et al. (2013) and Hu et al. (2018). As the literature suggests (e.g. Akagi et al., 2011), there is large uncertainty regarding estimated emission factors, so implied estimates of land use-related air pollutant emissions should be used with caution.

Estimates suggest that in the case of all pollutants, over the analyzed time horizon, the highest emission levels were observed in 2004. Between 2004 and

2011, on average (over all nine pollutants), emissions from forests and organic soils burning have declined by 20%, but their level has increased by around 16% between 2011 and 2014. The share of non-GHG emissions from forests and organic soils burning is estimated to be around 25.4% of total non-GHG emissions.[11] The shares, though, vary largely by pollutant. For instance, in the case of OC, PM10 and PM2.5, these categories contributed over 40% of total non-GHG emissions, while in the case of NO_x and SO_2 the corresponding share is under 2%.

On average (over all pollutants and reference years), organic soils contribute almost 50% of all non-GHG emissions from forests and organic soils combustion (Table K.2, Appendix K). This share reaches 64% in the case of SO_2 and 80% in the case of NH_3. The rest of emissions are distributed almost equally between burning of tropical forests and other forests.

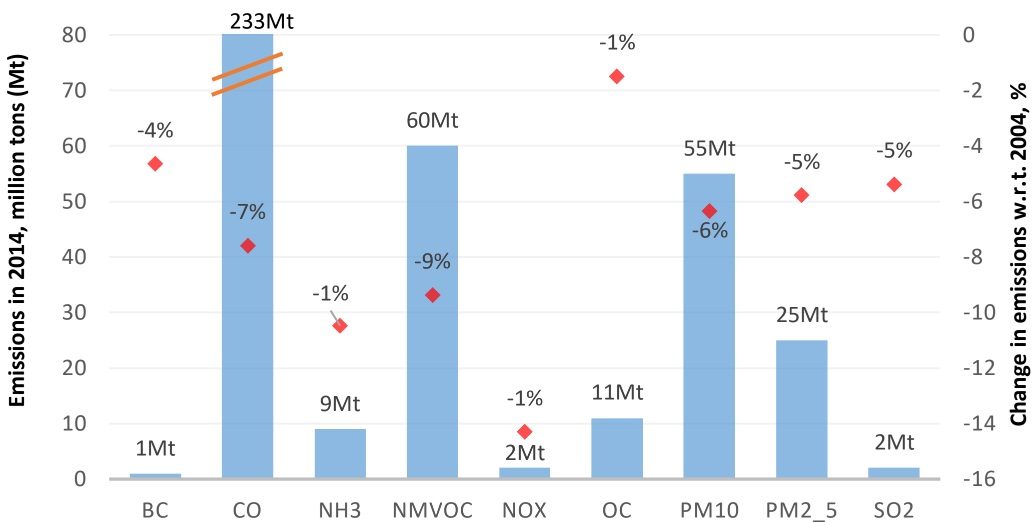

Figure 4. Global non-GHG emissions from forests and organic soils burning.

Notes: Columns represent the level of emissions in 2014 (primary vertical axis); diamonds report change in the level of emissions w.r.t. 2004 (secondary vertical axis).

Source: Estimated by author based on FAO (2020), Akagi et al. (2011), Yokelson et al. (2013) and Hu et al. (2018).

4. Overview of the air pollutant emissions database

In this section we provide an overview of the non-GHG emissions linked to the GTAP emission drivers, i.e. emissions that are not associated with the forests and organic soils burning. Over the 2004-2014 period global air pollutant emissions have been increasing steadily for all pollutants with the highest growth rates

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[11] A simple average estimate over four reference years.

observed for PM2.5 and BC (on average 2.1% per year), followed by PM10 (1.9% per year) and OC (1.5% per year) (Figure 5).

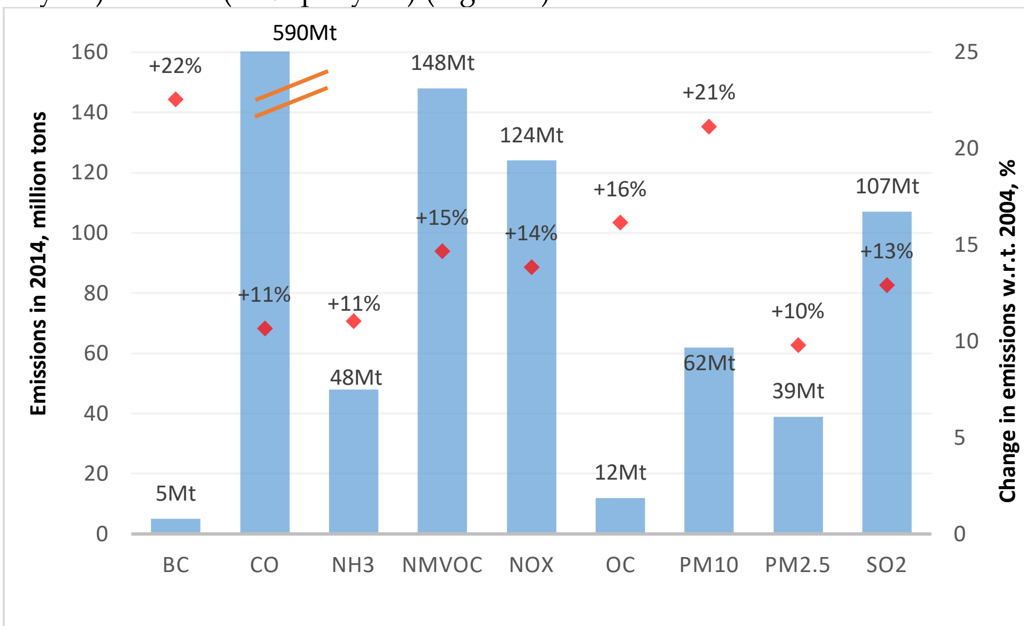

Figure 5. Global non-GHG emissions in 2014 by air pollutants

Notes: Emissions from forests and organic soils are not reported on this figure. The red diamond represents the percent changes in emission in 2014 relative to the 2004 levels.

Source: Estimated by author based on EDGAR v5.0 database (Crippa et al., 2020) and GTAP 10A air pollutant emissions database.

At the global level, consumption is the most common driver of pollution (Figure 6). In the case of all 9 air pollutants, intermediate and final consumption accounts for at least 56.4% of all emissions. Output is the second most important pollution driver for all substances. Only in the case of NH_3 emissions, the endowment driver provides a relatively substantial contribution (12%) to the total volume of emissions, with the corresponding emission flows being associated with land and capital inputs.

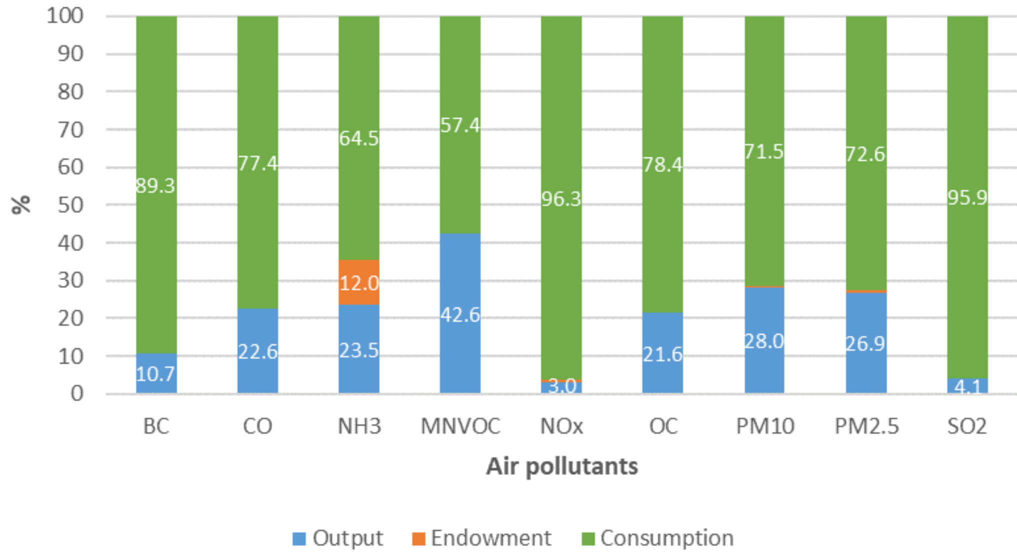

Figure 6. Global average distribution of air pollutants by source (2004, 2007, 2011 and 2014 weighted average).

Notes: Emissions from forests and organic soils are not reported in this figure.

Source: Author's estimates based on EDGAR v5.0 database (Crippa et al., 2020) and GTAP 10A air pollutant emissions database.

At the sectoral level, key emitters largely vary by air pollutants. In the case of six pollution categories (BC, CO, NMVOC, OC, PM10 and PM2.5), households are the key contributors, accounting for at least 22% of all emissions (Figure 7). Electricity generation activity is the largest contributor in the case of two pollutants (NO_x, and SO_2), reaching almost 46% in the case of SO_2 emissions. At the global level, contribution of the top five key emitting sectors ranges between 50% (for BC and PM10) to 76% (for SO_2 and NO_x) (Figure 7).

At the regional level, contribution by users differs significantly across countries. For instance, in the case of SO_2 emissions, electricity generation ("ely") contributes over 78% in the U.S., while in a number of other countries, such as Singapore, Belgium, Cyprus, Denmark, Estonia, Greece, Latvia, Netherlands and Norway, water transportation activity accounts for at least 70% of all SO_2 emissions.

Comparison of the constructed emissions database with other selected air pollutant emission datasets (Lamarque et al., 2010; van Vuuren et al., 2011; Hoesly et al., 2018) is provided in Appendix L.

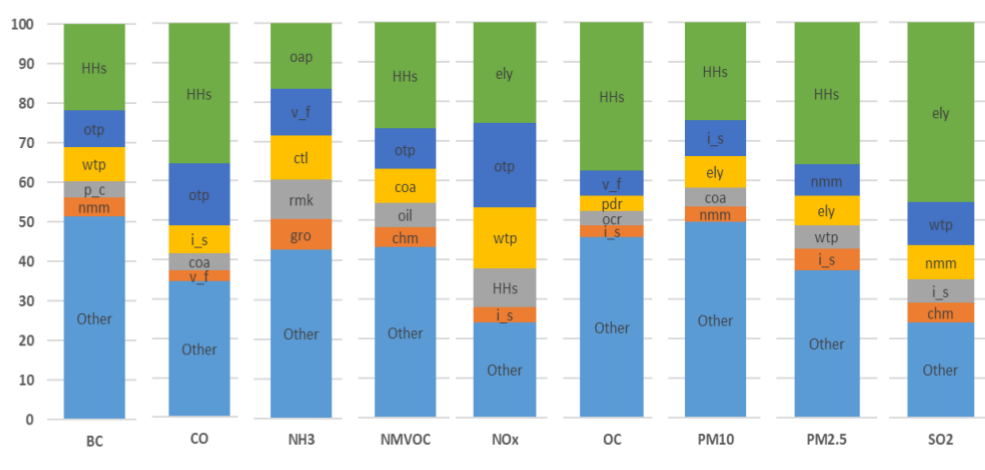

Figure 7. Distribution of global emissions by users, % (2004, 2007, 2011 and 2014 weighted average).

Notes: The top five contributors are explicitly identified for each pollutant, the rest of the users are labeled "Other". Sectoral labels follow definitions provided in Appendix M. "HHs" stands for households. Emissions from forests and organic soils are not reported in this figure.

Source: Author's estimates based on GTAP 10A air pollutant emissions database.

5. Numerical illustration: primary PM2.5 emissions embodied into trade

Adverse health impacts of PM2.5 emissions are well recognized in the literature (Nasai et al., 2020; Xing et al., 2016; Feng et al., 2016). This is especially the case for developing countries, such as China and India, where both domestic consumption and exports of commodities have been rapidly increasing over the last years (UN, 2020). According to Zhang et al. (2017), in 2007 around 22% of premature deaths caused by PM2.5 were associated with goods and services produced in one region for consumption in another.

In this section, we explore temporal, sectoral and regional patterns of the primary PM2.5 emissions embodied in bilateral trade (EEBT). Similar analyses, though with a different time coverage and based on a different underlying data have been conducted in Meng et al. (2019) and Moran and Kanemoto (2016). In the current assessment we exclude land use emissions (discussed in Section 3.4), as these emissions are not linked to value flows in the air pollutant emissions database. To estimate the EEBT flows, we follow an approach discussed in Peters (2008), which we briefly outline below.[12]

Country-specific PM2.5 emissions per unit of output across sectors are used to estimate emissions associated with bilateral trade flows. It is assumed that in a

[12] A discussion of different frameworks for comparing emissions associated with production, consumption and international trade can be found in Kanemoto et al. (2012).

given sector and country the same technology is used to produce domestic and exported commodities. For every sector of the economy, PM2.5 emissions embodied in trade from region r to regions s (f_{rs}) are estimated as $f_{rs} = F_r(I - A_r)^{-1}e_{rs}$, where F_r is a vector of country-specific PM2.5 emissions per unit of output by industry, I is the identity matrix, A_r is the technological matrix, which represents the industry requirements of domestically produced products in region r and e_{rs} corresponds to the bilateral trade flow from region r to region s.

In 2014, out of 38,400 Gg of PM2.5 emitted globally, 20.4% was associated with international trade – a decline of 1.8 percentage points from the 2007 levels (peak share over the analyzed period). Over 23% of all PM2.5 EEBT in 2014 was associated with exports from China, which is a country with the world's largest volume of PM2.5 emissions embodied in its exports (Figure 8). USA is a country with the largest volume of PM2.5 emissions embodied in its imports. Though in both country cases the contribution to global EEBT has decreased substantially since 2004 (Figure 8). A number of developing countries, including India and South Africa, have significantly increased their PM2.5 emissions embodied in net exports between 2004 and 2014, as India became the second largest country after China in terms of PM2.5 emissions embodied in net exports (with an unprecedented increase of 108% since 2004).

The sectoral composition of PM2.5 emissions embodied in net exports varies largely by country (Figure 8). While for China and USA, manufacturing activities (excluding energy intensive industries) represent the largest share, in the case of Brazil, PM2.5 EEBT are associated mostly with agricultural and food commodities; in the case of Greece almost all PM2.5 embodied in net exports are associated with (transportation) services. In countries like India, South Korea and Japan, PM2.5 emissions embodied in net exports are rather uniformly distributed across the four aggregated sectors identified in Figure 8.

The PM2.5 emission intensities of exports (for net exporters) and imports (for net importers) are largely driven by the composition of trade flows. For instance, Greece, which is a large exporter of transportation services, has the highest PM2.5 intensity of exports among the reported countries (3.9 kg per 1 USD). At the same time, China with a high share of light manufacturing goods in its total exports has a much lower emission intensity – 0.9 kg per 1 USD (Figure 8).

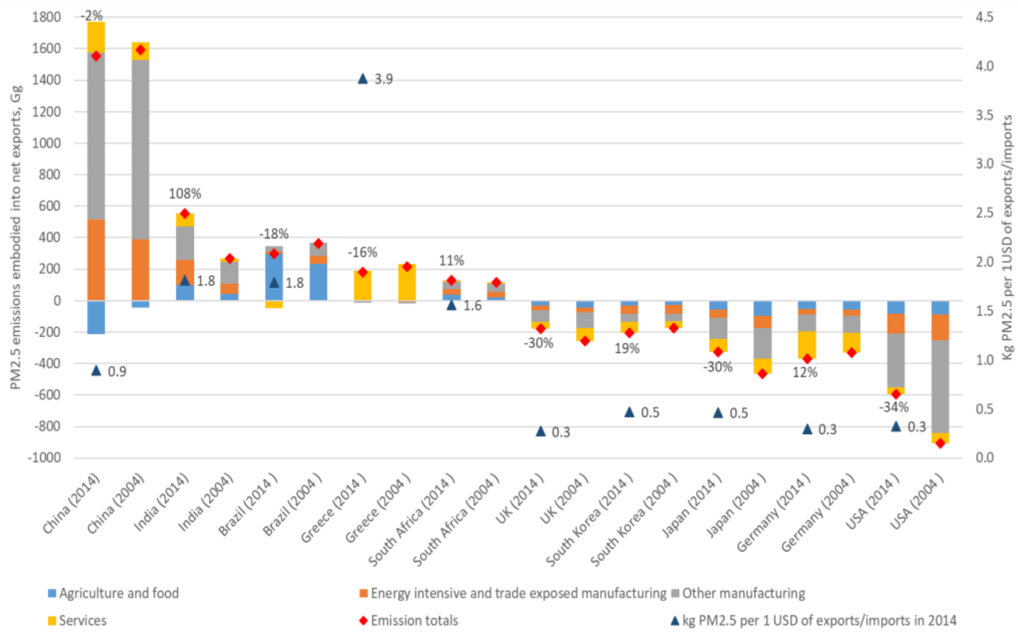

Figure 8. PM2.5 emissions embodied in net exports for selected countries, Gg.

Notes: The top five countries with the largest volumes of PM2.5 EEBT (based on the 2014 flows) are reported in the figure. Data callouts indicate percentage changes in 2014 flows relative to 2004 levels. Stacked bars indicate PM2.5 emissions decomposition by four aggregate sectors13. Red diamonds represent emission totals over all sectors. Dark blue triangles report PM2.5 intensities of exports (for net exporters – China, India, Brazil, Greece and South Africa) and imports (for net importers – UK, South Korea, Japan, Germany and USA) in kg per 1 USD based on the 2014 data (plotted on the secondary vertical axis).

Source: Developed by author.

Significant shifts have also occurred in terms of the regional destination of the PM2.5 EEBT flows between 2004 and 2014 (Figure 9). In particular, China has shifted its PM2.5-intensive exports away from USA and Japan toward India and Brazil. The EU became the largest destination of Chinese PM2.5-intensive exports, overtaking USA. Both USA and EU have shifted their imports of PM2.5-intensive commodities towards India, redirecting away from China. Two key destinations

[13] The following sectoral aggregation is used for the reporting: Agriculture and food (pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh, cmt, omt, vol, mil, pcr, sgr, ofd, b_t); Energy intensive and trade exposed manufacturing (chm, rpp, nmm, i_s, nfm); Other manufacturing (coa, oil, gas, oxt, tex, wap, lea, lum, ppp, p_c, bph, fmp, ele, eeq, ome, mvh, omf); Services (ely, gdt, wtr, cns, trd, afs, otp, wtp, atp, whs, cmn, ofi, ins, rsa, obs, ros, osg, edu, hht, dwe). The full list of the GTAP 10a Data Base sectoral codes is available at: https://www.gtap.agecon.purdue.edu/databases/v10/v10_sectors.aspx#Sector65 and in Appendix M.

for Indian exports expansion include USA and EU. South Africa has redirected its PM2.5 embodied in exports from EU toward China.

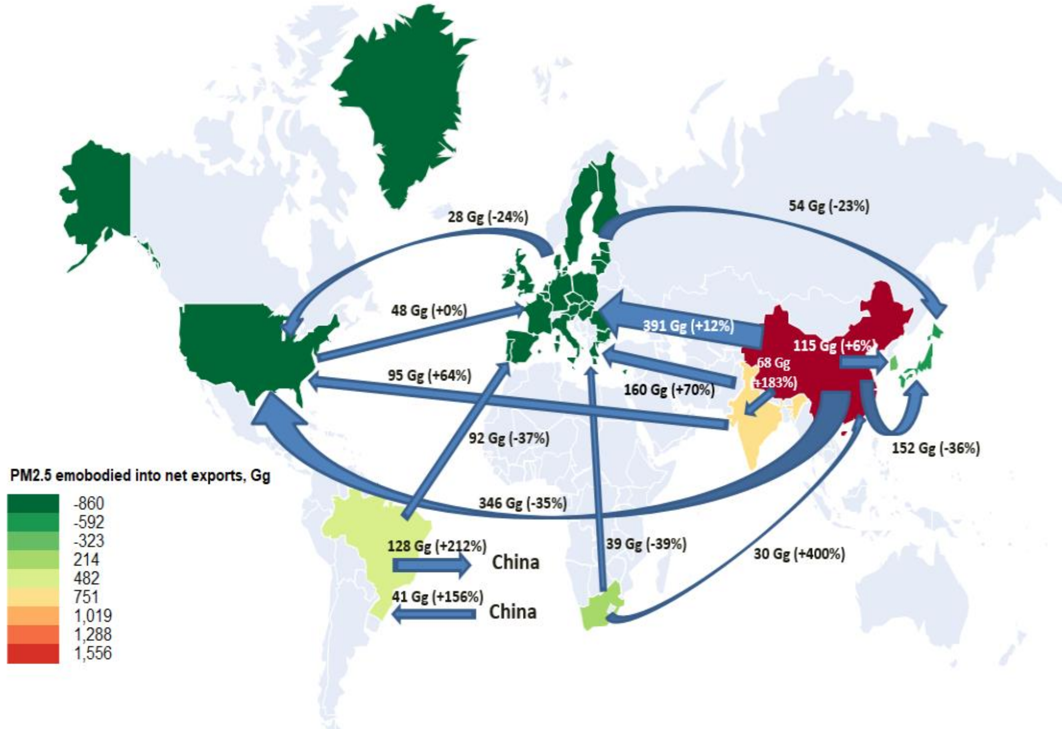

Figure 9. PM2.5 EEBT flows for selected countries and regions in 2014, Gg per year.

Notes: Reported net PM2.5 exporters include China, India, South Africa and Brazil; net PM2.5 importers include USA, EU-28, Japan and South Korea. Numbers in brackets indicate percentage changes in corresponding flows relative to 2004 levels. Non-reported regions are shaded in light grey. EU-28 is represented on the figure as a single entity.

Source: Developed by author.

In the context of sectoral distribution, most of the PM2.5 EEBT flows are associated with transportation activities, though the share has decrease by 0.2 percentage points since 2004 reaching 22.8% in 2014 (Figure 10). The share of PM2.5 EEBT flows from agriculture and food sectors, on the contrary, has been rapidly increasing and reached 19.8% in 2014. Metals production is another activity with growing PM2.5 exports. Sectors with rapidly decreasing contributions to global PM2.5 EEBT flows include other manufacturing and textiles (Figure 10).

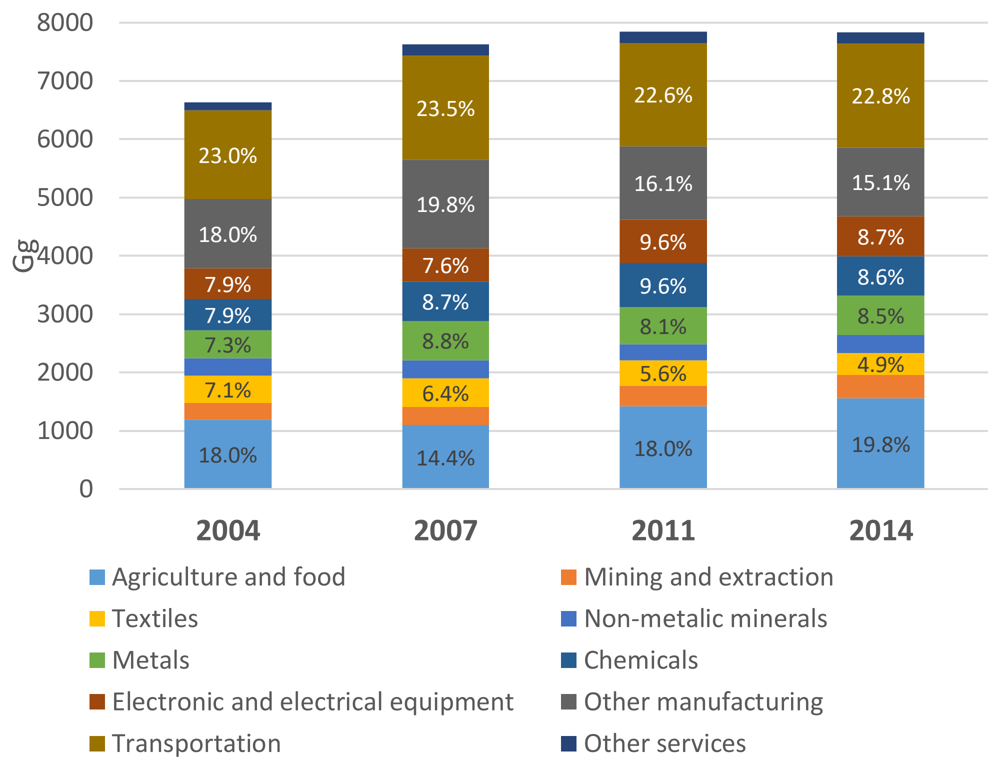

Figure 10. Sectoral decomposition of PM2.5 EEBT flows, Gg per year.

Source: Estimated by author.

6. Summary and discussion

With a major contribution to premature mortality and morbidity levels, ambient air pollutant emission is one of the most severe global health risk factors (Cohen et al., 2017). Representation of air pollutant emission flows in global economic models is thus an important element of a consistent assessment of health and environmental policies. Yet, not all global economic models include such data. In this paper we develop the methodology to produce a global air pollutant emissions dataset consistent with the GTAP Data Base, one of the most widely used databases for the global economic analysis (Aguiar et al., 2019). The air pollutant emission accounts are largely based on the EDGAR v5.0 database (Crippa et al., 2020), include four reference years (2004, 2007, 2011 and 2014), cover 141 regions and 65 sectors. Emissions are linked to economic activities and three sets of emission sources: consumption (by intermediate and final users), endowment use (land) and output. The air pollutant emissions database enables easy integration with GTAP-based CGE models, as well as facilitating downstream linkages to existing global atmospheric source-receptor models, such as TM5-FASST (Van Dingenen et al., 2018). In addition to non-land use sources, emissions from land use activities are estimated by land cover type, based on the volumes of burned biomass and emission factors.

As an illustrative application, we use the constructed database to track PM2.5 emissions embodied in international trade. We show that the global share of PM2.5 emissions embodied in trade has decreased from 21.2% in 2004 to 20.4% in 2014, though increasing in absolute terms by 18% over the same period. Between 2004 and 2014 China (the country with the largest volume of PM2.5 embodied in exports) and USA (country with the largest volume of PM2.5 embodied in imports) have significantly reduced their shares in global PM2.5 EEBT – by 15% and 37% respectively (in net terms). At the same time, several developing countries have rapidly increased their contribution to PM2.5 EEBT, including such net exporters as India (+109%), Thailand (+21%) and South Africa (+16%). In terms of the sectoral distribution, most PM2.5 embodied in trade is associated with transportation activities, though its share has decreased by 0.2 percentage points since 2004 reaching 22.8% in 2014. The share of PM2.5 EEBT from agriculture and food sectors, on the contrary, has been rapidly increasing and reached 19.8% in 2014. Metals production is another activity with growing PM2.5 EEBT. Sectors with rapidly decreasing contributions to global PM2.5 EEBT flows include other manufacturing (-2.9 percentage points) and textiles (-2.2 percentage points).

In terms of the potential applications, the air pollutant database can be directly linked to GTAP-based computable general equilibrium models to explore a wide range of policy questions. In addition, the air pollutant accounts can be merged with the GTAP multi-region input-output (MRIO) framework (Carrico, 2017; Carrico et al., 2020) to be used for detailed analyses of consumption-based emissions. Another potential extension includes linking of the air pollution accounts to the GTAP-Power Data Base (Chepeliev, 2020b), as illustrated in Taheripour et al. (2021). While readily suitable for static analysis, use of the database for dynamic simulations requires additional assumptions on changes in emission intensities over time—across regions, end-users and drivers.

While the development of the database described in this paper provides a step towards broader incorporation of environmental accounts in input-output and computable general equilibrium modelling frameworks, several limitations and potential improvements should be highlighted.

First, in the process of associating emission sources with the GTAP users and drivers, specific mapping assumptions have been developed. Though the mappings have been developed based on the best available information, some subjective assumptions have been introduced. This is especially the case for emissions that are not related with fossil fuel combustion. These assumptions could be further challenged and revised based on additional information.

Second, in the case of pollution from fuel combustion, emissions are associated with only four energy commodities – coal, oil, gas and petroleum products.

Biofuels and waste combustion are ignored under the current set up, as their energy content is not separately identified in the GTAP Data Base. Introduction of the bio-derived energy volumes to the GTAP energy dataset would provide a better opportunity for representing emissions from biomass and biofuels combustion.

Third, while emissions from savanna and field burning of agricultural residues are represented in the EDGAR database, emissions from the large scale biomass burning and activities of land use, land-use change and forestry are not reported in EDGAR. Additional data sources have been used to complement the GTAP air pollutant emissions database with emissions from forests and organic soils burning, improving the representation of global non-GHG emissions. At the same time, in the database, these emissions are reported separately, i.e. are not linked to specific emission drivers. Further research could be undertaken to link these emissions to model-based variables.

Fourth, to provide a more accurate allocation of emissions between different types of fossil fuel consumption by industry and households we use the emission factors collected from multiple data sources. However, the incorporated emission factors are not always country and agent-specific. Incorporation of a more detailed (country-, agent- and fuel-specific) emission factors is one of the potential future improvements, which the database could benefit from.

Finally, in terms of the modelling application, the dataset provides links between emission flows, drivers and activities. Therefore, changes in the level of economic activities (output, consumption, endowment use) resulting from a specific policy simulation could be directly linked to changes in emission volumes. At the same time, the database does not provide any information on the cost of reducing the emission of pollutants, which is important for the consistent assessment of emission reduction measures. Development of marginal abatement cost curves (MACCs) for the reported air pollutants could be an important addition to the dataset.

Data availability statement

GTAP 10 air pollutant emissions Data Base is available free of charge to all GTAP 10 Data Base subscribers, data contributors and GTAP board members. For more details please visit https://www.gtap.agecon.purdue.edu/.

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Appendix A. Global emissions distribution by IPCC categories and pollution substances in the EDGAR 5.0 database[15]

IPCC code	Air pollutant emissions source description	Emission substances (2004-2014 average shares, %)								
		BC	*CO*	*NH_3*	*NMVOC*	*NO_x*	*OC*	*PM10*	*PM2.5*	*SO_2*
1A1a	Public electricity and heat production	2.1	1.2	0.2	0.5	**25.4**	0.9	7.4	7.0	**45.2**
1A1bc	Other Energy Industries	**10.5**	0.5	0.0	0.2	2.3	0.8	3.2	3.7	4.2
1A2	Manufacturing Industries and Construction	**22.2**	9.6	1.4	6.7	**16.7**	**14.9**	**16.9**	**23.3**	**27.8**
1A3a	Domestic aviation	0.1	0.1	0.0	0.0	0.9	0.0	0.0	0.1	0.1
1A3b_NORES	Road transportation (no resuspension)	10.0	**34.1**	1.5	**19.7**	**26.2**	3.2	1.7	2.8	0.8
1A3b_RES	Road transportation (resuspension)	0.4	0.0	0.0	0.0	0.0	0.4	1.0	0.8	0.0
1A3c	Rail transportation	0.5	0.1	0.0	0.1	1.6	0.3	0.5	0.7	0.1
1A3d	Inland navigation	2.4	0.8	0.0	0.6	2.9	0.5	1.0	1.6	2.2
1A3e	Other transportation	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.1
1A4	Residential and other sectors	**32.3**	**30.4**	7.8	**17.3**	4.6	**55.9**	**42.0**	**37.4**	6.4
1A5	Other Energy Industries	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1
1B1	Fugitive emissions from solid fuels	4.8	6.7	2.1	**12.2**	0.0	0.3	6.9	1.6	0.0
1B2	Fugitive emissions from oil and gas	0.0	0.1	0.0	**13.6**	0.1	0.0	0.0	0.0	0.0
1C1	Memo: International aviation	0.1	0.0	0.1	0.1	1.7	0.0	0.1	0.1	0.2
1C2	Memo: International navigation	6.1	0.1	0.0	0.4	**12.5**	1.3	2.6	4.1	8.6
2A1	Cement production	0.6	0.0	0.0	0.0	0.0	0.0	2.4	2.7	0.0
2A2	Lime production	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.8	0.0
2A4	Production of other minerals	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
2A7	Other (Mineral products)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2B	Production of chemicals	0.0	0.0	0.4	1.3	0.1	0.0	0.1	0.2	1.0
2C	Production of metals	0.0	6.8	0.0	0.3	0.0	0.0	1.0	0.8	1.3
2D	Production of pulp/paper/food/drink	0.0	0.2	0.0	1.4	0.1	0.0	1.2	0.3	1.1

[15] IPCC codes 1B1x and 1B2x are aggregated with 1B1 (Solid fuels) and 1B2 (Oil and natural gas) respectively. Codes 1B1x and 1B2x are not reported in the IPCC source/sink categories. 1A3b_NORES and 1A3b_RES correspond to the road transportation emissions without and with resuspension respectively. IPCC source/sink categories report 1A3b code only.

IPCC code	Air pollutant emissions source description	Emission substances (2004-2014 average shares, %)								
		BC	*CO*	*NH_3*	*NMVOC*	*NO_x*	*OC*	*PM10*	*PM2.5*	*SO_2*
2G	Non-energy use of lubricants/waxes (CO_2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3A	Solvent and other product use: paint	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0	0.0
3B	Solvent and other product use: degrease	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
3C	Solvent and other product use: chemicals	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
3D	Solvent and other product use: other	0.0	0.0	0.0	**11.6**	0.0	0.0	0.0	0.0	0.0
4B	Manure management	0.0	0.0	**23.7**	3.6	0.3	0.0	2.8	0.8	0.0
4C	Rice cultivation	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0
4D1	Direct soil emissions	0.0	0.0	**40.3**	0.0	1.8	0.0	0.0	0.0	0.0
4D2	Manure in pasture/range/paddock	0.0	0.0	**14.2**	0.0	0.7	0.0	0.1	0.1	0.0
4D4	Other direct soil emissions	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
4F	Agricultural waste burning	6.8	8.7	2.8	2.6	1.5	**21.1**	6.4	9.8	0.2
6A	Solid waste disposal on land	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
6B	Wastewater handling	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
6C	Waste incineration	0.2	0.0	0.2	1.6	0.1	0.1	0.4	0.4	0.1
6D	Other waste handling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7A	Fossil fuel fires	0.6	0.5	0.0	0.1	0.0	0.1	0.4	0.4	0.3
	Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Notes: cases with shares greater than 10% are highlighted bold.

Source: estimated by authors based on EDGAR 5.0 (Crippa et al., 2020).

Appendix B. Mapping between EDGAR air pollutant emission sources, emission drivers and GTAP sectors

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	2	3	4	5	6	7	8
1	1A1a	Public electricity and heat production	Consumption (coa, oil, gas, gdt, p_c)	40	Mapped to the electricity sector as heat production in GTAP is part of the electricity sector	ely	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
2	1A1bc	Other Energy Industries	Consumption (coa, oil, gas, gdt, p_c)	10, 11, 23, 27 (40)	ISIC 40 is excluded as a non-primary source for this category. ISIC 27 emissions are attributed to 1A2 only.	coa, oil, gas, p_c, gdt	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
3	1A2	Manufacturing Industries and Construction	Consumption (coa, oil, gas, gdt, p_c)	15-22, 24-37, 45 (10-14, 23)	ISIC 10-11 and 23 are excluded as non-primary sources and to avoid overlapping with 1A1bc. ISIC 12-14 are included to complement sectoral coverage of 1A1a and 1A1bc.	oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
4	1A3a	Domestic aviation	Consumption (coa, oil, gas, gdt, p_c)	62	1-to-1 correspondence with GTAP sector	atp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)

[16] ISIC Rev. 3.1 codes are derived from Eurostat (2015), unless otherwise noted. ISIC codes in round brackets suggest possible (non-primary) mapping.
[17] GTAP use sources include 65 sectors and households.

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
5	1A3b_NORES	Road transportation (no resuspension)	Consumption (coa, oil, gas, gdt, p_c)	01-99, H. transport	Emissions are attributed to Other transportation and households	otp, HHs[18]	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
6	1A3b_RES#	Road transportation (resuspension)	Output		Emissions are linked to road transportation only	otp	
7	1A3c	Rail transportation	Consumption (coa, oil, gas, gdt, p_c)	60	1-to-1 correspondence with GTAP sector	otp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
8	1A3d	Inland navigation	Consumption (coa, oil, gas, gdt, p_c)	61, 05	While Eurostat (2012) maps ISIC 05 into 1A3d category, IPCC guidelines (Houghton et al, 1997) excludes fishing from 1A3d category.	wtp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
9	1A3e	Other transportation	Consumption (coa, oil, gas, gdt, p_c)	60	1-to-1 correspondence with GTAP sector. Mainly pipeline transport and non-specified transportation.	otp	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
10	1A4	Residential and other sectors	Consumption (coa, oil, gas, gdt, p_c)	01-05, 50-99 (40), Households	ISIC 40 is excluded as non-primary source. Transport sectors are excluded as non-primary contributors. ISIC 41 is added for water distribution activities coverage	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh, wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros,	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)

[18] In the case of households, 1A3B emissions are linked to the "p_c" use only.

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	2	3	4	5	6	7	8
						osg, edu, hht, dwe, HHs[19]	
11	1A5	Other	Consumption (coa, oil, gas, gdt, p_c)	50-99, (40)	ISIC 40 is excluded as non-primary source. Transport sectors are excluded as non-primary contributors. ISIC 41 is added for water distribution activities coverage	wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe	Energy use data; emission factors (Coady et al., 2015; IPCC, 2017)
12	1B1#	Fugitive emissions from solid fuels	Output	10, 23, 27 (24, 26, 40)	Mainly associated with coal, mapped only to ISIC 10 (in line with Irfanoglu and van der Mensbrugghe, 2015)	coa[20]	Direct attribution
13	1B2#	Fugitive emissions from oil and gas	Output	11, 23, 40, 50, (60, 63)	Emission is associated only with ISIC 11, 23 and 40. Due to the highly aggregated trade sector ("trd") in GTAP Data Base, we exclude ISIC 50 code from mapping.	gas, oil, gdt, p_c	Distribute proportionally to output
14	1C1	Memo: International aviation	Consumption (coa, oil, gas, gdt, p_c)	62*		atp	Distributed by regions based on the value of exports[21]
15	1C2	Memo: International navigation	Consumption (coa, oil, gas, gdt, p_c)	61*		wtp	Distributed by regions based on the value of exports

[19] In the case of households, 1A4 emissions are linked to the use of "coa", "oil", "gas" and "gdt".
[20] For a number of country cases, in particular in Africa, relatively large 1B1 emissions are associated with small values of coal and/or coke output, leading to the emission intensities of the corresponding flows being over 1000 times higher than the world average. For these specific country cases we have redistributed 1B1 emissions between coa, oil, gas, p_c, gdt and ely uses.
[21] Fugitive emissions from international navigation are mapped to the fuel use in water transportation sector.

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
16	2A1#	Cement production	Output	26		nmn	Direct attribution
17	2A2#	Lime production	Output	26		nmn	Direct attribution
18	2A4#	Production of other minerals	Output	26		nmn	Direct attribution
19	2A7#	Other (mineral products)	Output	26		nmn	Direct attribution
20	2B#	Production of chemicals	Output	24	Taking into account GTAP sectoral splits, all emissions are attributed to ISIC 24.1, 24.2	chm	Direct attribution
21	2C#	Production of metals	Output	27		i_s, nfm	Distributed proportionally to output values
22	2D#	Production of pulp/paper/food/drink	Output	15, 20, 21		cmt, omt, vol, mil, pcr, sgr, ofd, b_t, lum, ppp	
23	2G#	Non-energy use of lubricants/waxes	Consumption of chemical products	-		All sectors, including HHs	Distributed proportionally to chemical products use
24	3A#	Solvent and other product use: paint	Consumption of chemical products	20-22, 24-36, 45, 50, H. other	ISIC 24.3 is excluded as it is a minor part of "tex" sector	lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns, trd, afs, HHs	Distributed proportionally to chemical products use
25	3B#	Solvent and other product use: degrease	Consumption of chemical products	27, 28, 32, 93		i_s, nfm, fmp, ele, ros	Distributed proportionally to chemical products use

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	2	3	4	5	6	7	8
26	3C#	Solvent and other product use: chemicals	Consumption of chemical products	17, 19, 24, 25, 45		tex, lea, chm, bph, rpp, cns	Distributed proportionally to chemical products use
27	3D#	Solvent and other product use: other	Consumption of chemical products	15, 20, 22, 26, 34-36, 50, 85, H. other		b_t, lum, ppp, nmm, mvh, otn, omf, trd, afs, osg, edu, hht, HHs	Distributed proportionally to chemical products use
28	4B#	Manure management	Output	01		ctl, oap, rmk	Distributed proportionally output
29	4C#	Rice cultivation	Endowment (land)	01		pdr	Direct mapping
30	4D1#	Direct soil emissions	Consumption of chemical products	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to chemical products consumption
31	4D2#	Manure in pasture/range/ paddock	Endowment (capital)	01		ctl, oap, rmk	Distributed proportionally to capital use
32	4D4#	Other direct soil emissions	Consumption (chm)	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to chemical products consumption
33	4F#	Agricultural waste burning	Output	01		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to sectoral output

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	ISIC Rev. 3 code[16]	Comments on sectoral mapping	GTAP 10 use sources[17] mapping	Source for emissions distribution
1	2	3	4	5	6	7	8
34	6A#	Solid waste disposal on land	Output	75, 90		wtr	Direct mapping
35	6B#	Wastewater handling	Output	10-45, 90	ISIC 90 is assumed to be key contributor, others are ignored	wtr	Direct mapping
36	6C#	Waste incineration	Output	01, 10-37, 75, 90, 93	Agricultural sectors are excluded and it is assumed that all agricultural waste burning is associated with 4F	coa, oil, gas, oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, p_c, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, wtr	Distributed proportionally to sectoral output
37	6D#	Other waste handling	Output	01, 90		pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, wtr	Distributed proportionally to sectoral output
38	7A#	Fossil fuel fires	Output		Fossil-fuel fires are assumed to be mainly associated with coal mining and oil extraction	coa, oil	Distributed proportionally to sectoral output

Notes: *Authors' assumptions on coding; # indicates IPCC categories with emission distribution based on GTAP value data.

Source: Developed by authors.

Appendix C. Mapping between EDGAR air pollutant emission sources, PM2.5 bio emission drivers and GTAP sectors

No.	IPCC 1996 code	Air pollutant emissions source description	Emission driver	Comments on sectoral mapping (ISIC 3.1 codes are reported)	GTAP 10 use sources mapping	Source for emissions distribution
1	**2**	**3**	**4**	**6**	**7**	**8**
1	1A1a#	Public electricity and heat production	Consumption (frs, lum)	Mapped to the electricity sector as heat production in GTAP is part of the electricity sector	ely	Distributed proportionally to intermediate consumption
2	1A1bc#	Other Energy Industries	Consumption (frs, lum)	ISIC 40 is excluded as a non-primary source for this category. ISIC 27 emissions are attributed to 1A2 only.	coa, oil, gas, p_c, gdt	Distributed proportionally to intermediate consumption
3	1A2#	Manufacturing Industries and Construction	Output	ISIC 10-11 and 23 are excluded as non-primary sources and to avoid overlapping with 1A1bc. ISIC 12-14 are included to complement sectoral coverage of 1A1a and 1A1bc. Output is used as the main driver to avoid instances of non-energy intermediate use in specific sectors (e.g. "frs" and "lum" use in construction industry)	oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns	Distributed proportionally to output
4	1A4#	Residential and other sectors	Consumption (frs)	Literature suggests that in the case of residential and other non-agricultural sectors, the main source of PM2.5 bio emissions in the major emitting countries – China, India and Nigeria – is the households' consumption of the solid biomass for cooking and heating purposes (Zhang and Cao, 2015; Nagar et al., 2017; Chowdhury et al., 2019). Therefore 1A4 emissions are mapped to households' consumption of the solid biomass ('frs') in the GTAP framework.	HHs	Distributed proportionally to consumption

No.	**IPCC 1996 code**	**Air pollutant emissions source description**	**Emission driver**	**Comments on sectoral mapping (ISIC 3.1 codes are reported)**	**GTAP 10 use sources mapping**	**Source for emissions distribution**
1	**2**	**3**	**4**	**6**	**7**	**8**
5	1B1#	Fugitive emissions from solid fuels	Output	Following IPCC (2019), four sources of fugitive emissions for biomass are identified, these include emissions arising during the production of charcoal and biochar, emissions during the production of wood pellets and emissions from the transformation of biomass into syngas, and, then into liquid hydrocarbons fuels.	chm, lum, gdt	Direct attribution
6	1C2#	Memo: International navigation	Consumption (p_c)	There are some small volumes of PM2.5_bio emissions associated with international navigation. These are assumed to be coming from combustion of bio fuel.	wtp	
7	4F#	Agricultural waste burning	Output		pdr, wht, gro, v_f, osd, c_b, pfb, ocr	Distributed proportionally to sectoral output
8	6C#	Waste incineration	Output	Agricultural sectors are excluded and it is assumed that all agricultural waste burning is associated with 4F	coa, oil, gas, oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, p_c, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, wtr	Distributed proportionally to sectoral output

Notes: *Authors' assumptions on coding; # indicates IPCC categories with emission distribution based on GTAP value data.

Source: Developed by authors.

Appendix D. Concordance between GTAP energy dataset industries and GTAP sectors

No.	GTAP energy dataset (EDS) use flows	Use flow names
1	Exp	Export
2	IntlMarBnkr	International marine bunkers
3	IntlAvBnkr	International aviation bunkers
4	Elect_Gen	Electricity generation
5	P_C_Transfm	Petroleum and coal transformation
6	Gas_Transfm	Gas transformation
7	Coal	Coal mines
8	CrudeOils	Crude oil
9	NatGas	Natural gas
10	IronXSteel	Iron and steel
11	ChemXPetro	Chemical and petrochemical
12	FidStok4CRP	Petrochemical feed-stocks
13	NonFeroMetal	Non-ferrous metals
14	NonMetalMinr	Non-metallic minerals
15	TranspEqpmt	Transport equipment
16	MachineryMf	Machinery
17	MiningXQuary	Mining and quarrying
18	FoodXTabaco	Food and tobacco
19	PapXPulpXPrn	Paper, pulp and printing
20	WoodXWudProd	Wood and wood products
21	ConstrctnInd	Construction
22	TextlXLether	Textile and leather
23	NonSpecfInd	Non-specified industry
24	DomAviaTrnsp	Domestic air transport
25	RoadTransp	Road transport
26	RailTransp	Rail transport
27	PipelnTransp	Pipeline transport
28	HomeOwnShips	Internal navigation
29	NonSpecTrnsp	Non-specified transport
30	AgriForFish	Agriculture, forestry and fishery
31	ComXPubServ	Commercial and public services
32	HouseHolds	Households
33	MilitaryUse	Military use

Source: Based on IEA (2017) and McDougall and Chepeliev (2021).

Appendix E. Concordance between disaggregated GTAP energy dataset (EDS) commodities and aggregated energy commodities reported in the standard GTAP Data Base

No.	GTAP EDS commodity code	GTAP EDS commodity description	Corresponding aggregated GTAP energy commodity
1	AntCoal	Anthracite	coa
2	CokCoal	Coking coal	coa
3	BitCoal	Other bituminous coal	coa
4	SubCoal	Sub-bituminous coal	coa
5	Lignite	Lignite	coa
6	PatFuel	Patent fuel	coa
7	OvenCoke	Coke oven coke	p_c
8	GasCoke	Gas coke	p_c
9	CoalTar	Coal tar	p_c
10	BKB	Brown coal briquettes	coa
11	GasWksGs	Gas works gas	gas
12	CokeOvGs	Coke oven gas	p_c
13	BlFurGs	Blast furnace gas	i_s
14	OGases	Other recovered gases	i_s
15	Peat	Peat	coa
16	PeatProd	Peat products	coa
17	OilShale	Oil shale and oil stands	oil
18	NatGas	Natural gas	gas
19	CrudeOil	Crude oil	oil
20	NGL	Natural gas liquids	gas
21	RefFeeds	Refinery feedstocks	p_c
22	Additive	Additives/blending components	crp
23	NonCrude	Other hydrocarbons	crp
24	RefinGas	Refinery gas	p_c
25	Ethane	Ethane	p_c
26	LPG	Liquefied petroleum gases	p_c
27	NonBioGaso	Motor gasoline excluding bio	p_c
28	AvGas	Aviation gasoline	p_c
29	JetGas	Gasoline type jet fuel	p_c
30	NonBioJetK	Kerosene type jet fuel excl. bio	p_c
31	OthKero	Other Kerosene	p_c
32	NonBioDies	Gas/diesel oil excluding bio	p_c
33	ResFuel	Fuel oil	p_c
34	Naphtha	Naphtha	p_c
35	WhiteSp	White spirit and industrial spirit (SPB)	p_c
36	Lubric	Lubricants	p_c
37	Bitumen	Bitumen	p_c
38	ParWax	Paraffin waxes	p_c
39	PetCoke	Petroleum coke	p_c
40	ONonSpec	Non-specified oil products	p_c
41	Electr	Electricity	ely
42	Heat	Heat	ely

Source: Based on IEA (2017) and McDougall and Chepeliev (2021).

Appendix F. Correspondence between IPCC categories and GTAP energy dataset commodities

IPCC category code	IPCC category description	GTAP EDS use flow code	GTAP EDS use flow description
1A3a	Domestic aviation	DomAviaTrnsp	Domestic air transport
1A3c	Rail transportation	RailTransp	Rail transport
1A3d	Inland navigation	HomeOwnShips	Internal navigation
1A3e	Other transportation	PipeInTransp	Pipeline transport
		NonSpecTrnsp	Non-specified transport
1C1	Memo: International aviation	IntlAvBnkr	International aviation bunkers
1C2	Memo: International navigation	IntlMarBnkr	International marine bunkers

Source: Author.

Appendix G. Correspondence between air pollutants with available emission factors and EDGAR dataset air pollutants

No.	EDGAR database pollutants	EDGAR database pollutant name	Air pollutants with available emission factors	Emission factors source
1	BC	Black carbon	PM2.5 + estimates of the BC share	Klimont (2007), Chow et al. (2011) and EEA (2019), Coady et al. (2015)
2	CO	Carbon monoxide	CO	IPCC (2017)
3	NH_3	Ammonia	NH_3	Battye et al. (1994)
4	NMVOC	Non-methane volatile organic compounds	Volatile organic compounds (VOCs)	Coady et al. (2015)
5	NO_x	Nitrogen oxides	NO_x	Coady et al. (2015)
6	OC	Organic carbon	PM2.5 + estimates of the OC share	Klimont (2007), Chow et al. (2011) and EEA (2019), Coady et al. (2015)
7	PM10	Particulate matter 10	PM2.5	Coady et al. (2015)
8	PM2.5	Particulate matter 2.5	PM2.5	Coady et al. (2015)
9	SO_2	Sulfur dioxide	SO_2	Coady et al. (2015)

Source: Author.

Appendix H. Correspondence between IPCC combustion-related categories in the IPCC emission factor database and GTAP sectors

No.	IPCC category code	IPCC category description	Fossil fuel combustion emission factors data availability for CO	GTAP use categories
1	1A	Fuel combustion activities	-	-
2	1A1	Energy industries	+	coa, oil, gas, p_c, ely, gdt
3	1A2	Manufacturing industries and construction	+	oxt, cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, chm, bph, rpp, nmm, i_s, nfm, fmp, mvh, otn, ele, eeq, ome, omf, cns
4	1A3A	Civil aviation	+	atp
5	1A3A1	International aviation (international bunkers)	-	-
6	1A3A2	Domestic aviation	-	-
7	1A3B_NORES	Road transportation (no resuspension)	+	otp
8	1A3C	Railways	+	otp
9	1A3D	Navigation	+	wtp
10	1A4A	Commercial/institutional	+ (database provides identical emission factors for all three IPCC categories)	wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe
11	1A4B	Residential		HHs
12	1A4C1	Stationary emission in agriculture/forestry/fishing		pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh
13	1A4C2	Off-road vehicles and other machinery emission in agriculture/forestry/fishing	-	-
14	1A5B	Other mobile emission	+	-

Source: Based on IPCC (2017).

Appendix I. Correspondence between IPCC database fuels and six energy commodities for air pollutant emission estimates

No	IPCC database fuel code	IPCC fuel code description	Air pollutant emissions database fuels
1	111	Wood/wood waste	-
2	112	Charcoal	-
3	205	Diesel oil	Diesel ("dsl")
4	208	Motor gasoline	Gasoline ("gsl")
5	301	Natural gas*	Gas extraction and distribution ("gas", "gdt")
6	302	Natural gas liquids*	-
7	318	Other bituminous coal*	-
8	322	Other oils	Oil ("oil")
9	329	Other solid biomass	-
10	S01	Undifferentiated coal*	Coal ("coa")

Notes: *Natural gas (301) and Natural gas liquids (302), as well as Other bituminous coal (318) and Undifferentiated coal (S01) have identical emission factors. Therefore, for the mapping purposes only one representative product from each pair is used.

Source: Based on IPCC (2017).

Appendix J. IPCC correspondence for additional air pollutants redistribution between GTAP users and drivers

No.	IPCC pollution categories with cases of zero-energy use data in GTAP Data Base and non-zero emissions in EDGAR database		IPCC pollution categories used for emissions redistribution	
1	X1A3a	Domestic aviation	X1A4	Residential and other sectors
2	X1A3d	Inland navigation	X1A4	Residential and other sectors
3	X1A1bc	Other Energy Industries	X1A2	Manufacturing Industries and Construction
4	X1A3c	Rail transportation	X1A3b_NORES	Road transportation (no resuspension)
5	X1A3e	Other transportation	X1A3b_NORES	Road transportation (no resuspension)

Source: Author.

Appendix K. Land use emissions: input data and assumptions

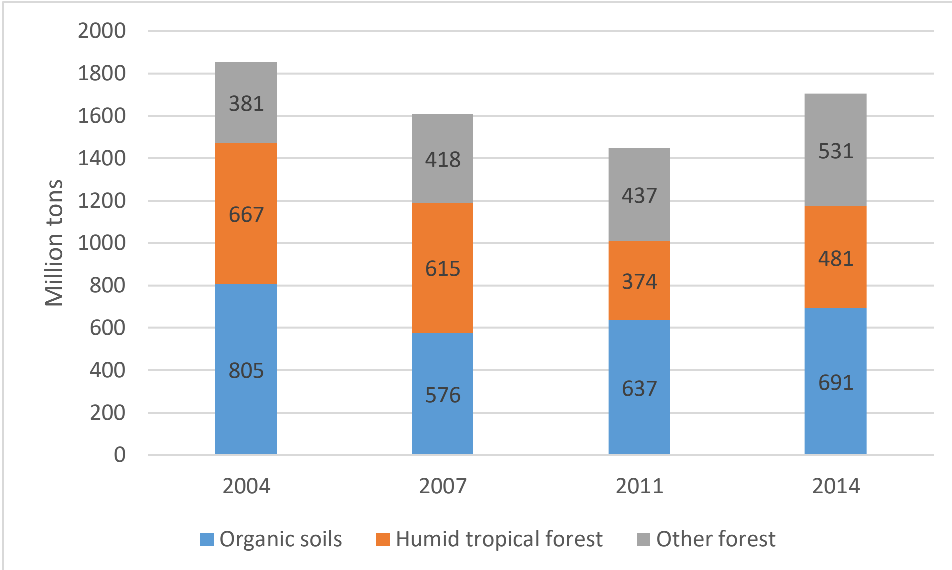

Figure K.1. Biomass burned (dry matter) by land cover types and years, million tons.

Source: FAO (2020).

Table K.1. Emission factors for biomass burning (dry matter), g kg^{-1}.

No.	Pollutant	Pollutant name	Organic soils	Humid tropical forest	Other forest
1	BC	Black carbon	0.20	0.52	0.56
2	CO	Carbon monoxide	182.00	93.00	122.00
3	NH_3	Ammonia	10.80	1.33	2.46
4	NMVOC	Non-methane volatile organic compounds	48.70	26.00	27.00
5	NO_x	Nitrogen oxides	0.80	2.55	1.12
6	OC	Organic carbon	6.23	4.71	9.15
7	PM10	Particulate matter 10	44.00*	18.50	30.49*
8	PM2.5	Particulate matter 2.5	19.17*	9.10	15.00
9	SO_2	Sulfur dioxide	1.76*	0.40	1.06*

Notes: Emission factors (EFs) not marked by "*" are sourced from Akagi et al. (2011). In the case of Other forest category, EFs for Extratropical forest are used, which represent a weighted average of boreal and temperate forest EFs (Akagi et al., 2011). SO2 EFs for Organic soils and Other forest categories are sourced from Yokelson et al. (2013). PM10 and PM2.5 EFs for Organic soils are sourced from Hu et al. (2018), using estimates for boreal and temperate peat. PM10 EF for Other forest is derived from PM2.5 emission factor assuming the same composition of particulate (i.e. ration of PM2.5 and PM10 EFs) as in the case of Humid tropical forest.

Source: Based on Akagi et al. (2011), Yokelson et al. (2013), Hu et al. (2018).

Table K.2. Emissions from biomass burning in 2014, million tons.

No.	Pollutant	Pollutant name	Organic soils	Humid tropical forest	Other forest
1	BC	Black carbon	0.3	0.3	0.1
2	CO	Carbon monoxide	44.8	63.0	125.7
3	NH_3	Ammonia	0.6	1.3	7.5
4	NMVOC	Non-methane volatile organic compounds	12.5	13.9	33.6
5	NO_x	Nitrogen oxides	1.2	0.6	0.6
6	OC	Organic carbon	2.3	4.7	4.3
7	PM10	Particulate matter 10	8.9	15.8	30.4
8	PM2.5	Particulate matter 2.5	4.4	7.7	13.2
9	SO_2	Sulfur dioxide	0.2	0.5	1.2

Source: Estimated by author.

Appendix L. Comparison of the emissions database with other data sources

To explore the consistency of the emission accounts, we have developed a comparison with several other available data sources at the global level. These include Representative Concentration Pathways (RCPs) database (van Vuuren et al., 2011), air pollutant emission accounts developed in Lamarque et al. (2010) and Hoesly et al. (2018). Considering that the latest data year reported in Lamarque et al. (2010) is 2000, the year 2000 was chosen for the data comparisons. It should be noted that the RCP database partly relies on the Lamarque et al. (2010), in particular, for the estimates of NO_x, CO, CH_4 and NMVOC emissions in all sectors, excluding grassland and forest fire, international shipping and aviation. Hoesly et al. (2018) estimates in many cases are scaled to match the EDGAR 4.2 and 4.3 emissions, as in the corresponding database construction process all countries are scaled first to EDGAR and then to individual estimates (Hoesly et al., 2018).

Comparisons show that significant differences between EDGAR 5.0 and the RCP database could be explained by the fact that EDGAR does not report emissions from large scale biomass burning and activities of land use, land-use change and forestry (Crippa et al., 2020). In the case of some pollutants (e.g. OC) forest and grassland burning activities contribute over 60% of all emissions (Figure L.1). Decomposition of the RCP emissions into forest burning, grassland burning and other sources, explains initially observed large discrepancies between EDGAR and the RCPs (Figure L.1). Once emissions from forest and organic soils burning are taken into account, based on the estimates developed in Section 3.4, initially observed differences are significantly reduced.

Hoesly et al. (2018) emissions are higher than the EDGAR v5.0 emissions (without large scale biomass burning), but in most cases are below the RCP estimates and EDGAR accounts with added biomass burning. Large uncertainty around biomass burning emission factors (Akagi et al., 2011) is one of the key underlying factors of the observed differences in emissions between different sources.

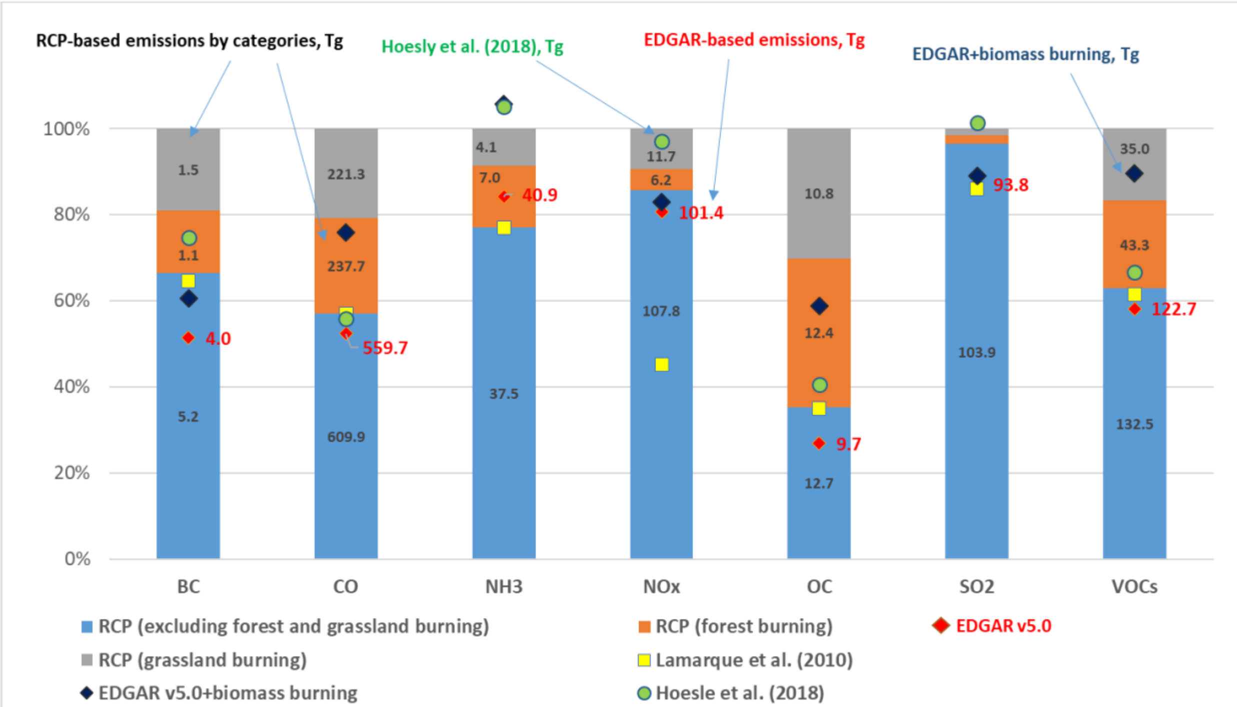

Figure L.1. Comparison of global emissions in 2000 based on different data sources.

Notes: All emission volumes are reported in Terragrams (Tg) (1 Tg equals 1 million metric tons). EDGAR-based emissions are represented using red rectangular; emissions reported in Lamarque et al. (2010) are represented using yellow squares; Hoesly et al. (2018) emissions are represented using green circles; emissions reported in the RCP database (van Vuuren et al., 2011) are represented using stacked columns. In the latter case, emissions are further decomposed into forest burning, grassland burning and other sources. Biomass burning emissions (from the year 2004) are added to the EDGAR v5.0 emissions and reported using blue rectangular. Percentages (left axis) measure emission volumes relative to the RCP database volumes (from all sources), which are assumed to equal 100%. For instance, in the case of organic carbon (OC), the RCP database reports that 10.8 Tg are emitted by grassland burning (account for around 35% of global OC emissions), 12.4 Tg by forest burning (35% of global emissions) and 12.7 Tg by other sources (30% of global emissions). Lamarque et al. (2010) reports global OC emissions of 12.6 Tg (excluding grassland and forest burning), which is around 30% of total OC emissions reported in the RCP database. EDGAR 5.0 reports global OC emissions of 9.7 Tg or around 27% of total emissions reported in the RCP database. OC emissions from forests and organic soils burning are 12.6 Tg or 35% of total RCP emissions.

Source: Author's estimates based on Lamarque et al. (2010), RCP database (van Vuuren et al., 2011) EDGAR v5.0 (Crippa et al., 2020) and Hoesly (2018).

But even for the non-land use-based emissions, some major revisions have been introduced between different database versions, in particular, between EDGAR v4.3.2 (Crippa et al., 2018) and EDGAR 5.0 (Crippa et al., 2020). In the case of some emission categories this has significantly impacted reported volumes. For five out of nine reported categories emissions have been reduced – between 0.5% for SO_2 and 13.5% for the case of NMVOC (Figure L.2). Revision of the BC emissions has resulted in their increase by around 9.1% for the year 2000.

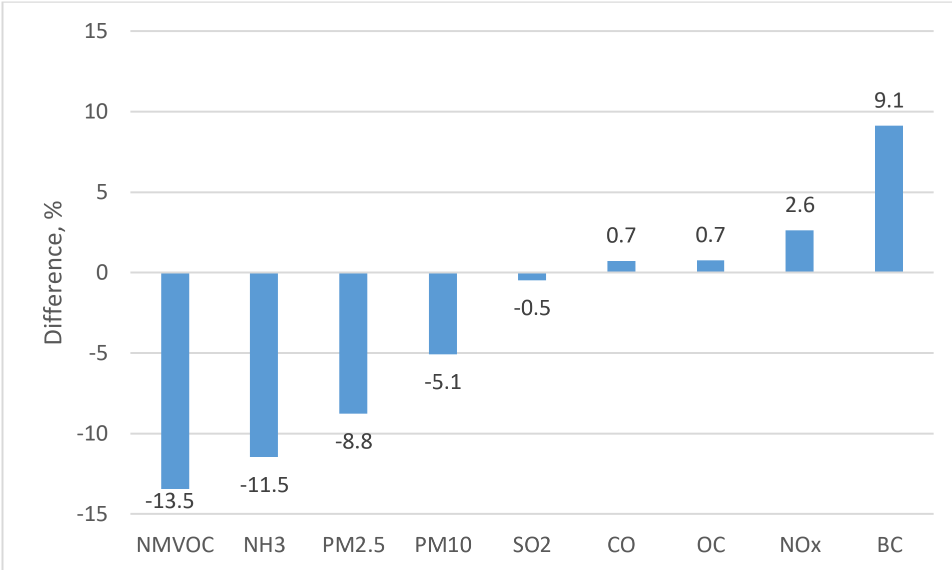

Figure L.2. Difference between global emissions reported in EDGAR v4.3.2 and EDGAR v5.0 for 2000 (v5.0 relative to v4.3.2 levels, i.e. negative numbers indicate that v5.0 emissions are lower than in v4.3.2).

Source: Estimated by author based on EDGAR v4.3.2 (Crippa et al., 2018) and EDGAR v5.0 (Crippa et al., 2020).

Appendix M. List of the GTAP 10A Data Base sectors

No.	Code	Description
1	pdr	Paddy rice
2	wht	Wheat
3	gro	Cereal grains nec
4	v_f	Vegetables, fruit, nuts
5	osd	Oil seeds
6	c_b	Sugar cane, sugar beet
7	pfb	Plant-based fibers
8	ocr	Crops nec
9	ctl	Bovine cattle, sheep and goats, horses
10	oap	Animal products nec
11	rmk	Raw milk
12	wol	Wool, silk-worm cocoons
13	frs	Forestry
14	fsh	Fishing
15	coa	Coal
16	oil	Oil
17	gas	Gas
18	oxt	Other Extraction
19	cmt	Bovine meat products
20	omt	Meat products nec
21	vol	Vegetable oils and fats
22	mil	Dairy products
23	pcr	Processed rice
24	sgr	Sugar
25	ofd	Food products nec
26	b_t	Beverages and tobacco products
27	tex	Textiles
28	wap	Wearing apparel
29	lea	Leather products
30	lum	Wood products
31	ppp	Paper products, publishing
32	p_c	Petroleum, coal products
33	chm	Chemical products
34	bph	Basic pharmaceutical products
35	rpp	Rubber and plastic products
36	nmm	Mineral products nec
37	i_s	Ferrous metals
38	nfm	Metals nec
39	fmp	Metal products
40	ele	Computer, electronic and optical products
41	eeq	Electrical equipment
42	ome	Machinery and equipment nec
43	mvh	Motor vehicles and parts
44	otn	Transport equipment nec
45	omf	Manufactures nec
46	ely	Electricity
47	gdt	Gas manufacture, distribution

No.	Code	Description
48	wtr	Water
49	cns	Construction
50	trd	Trade
51	afs	Accommodation, Food and service activities
52	otp	Transport nec
53	wtp	Water transport
54	atp	Air transport
55	whs	Warehousing and support activities
56	cmn	Communication
57	ofi	Financial services nec
58	ins	Insurance (formerly isr)
59	rsa	Real estate activities
60	obs	Business services nec
61	ros	Recreational and other services
62	osg	Public Administration and defense
63	edu	Education
64	hht	Human health and social work activities
65	dwe	Dwellings

Source: Aguiar et al. (2019).