# Development of the Air Pollution Database for the GTAP 10A Data Base

By

Maksym Chepeliev[1]

Research Memorandum No. 33

May 2020

[1] Research Economist at the Center for Global Trade Analysis, Purdue University. Email: mchepeli@purdue.edu.
I am grateful for the comments provided by Angel Aguiar and Dominique van der Mensbrugghe.

# Development of the Air Pollution Database for the GTAP Data Base Version 10A

**By Maksym Chepeliev**

**Abstract**

The purpose of this note is to document data sources and steps used to develop the air pollution database for the GTAP Data Base Version 10A. Emissions for nine substances 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 ($SO_2$). The dataset covers four reference years – 2004, 2007, 2011 and 2014. EDGAR Version 5.0 database is used as the main data source. To assist with emissions redistribution across consumption-based sources, IIASA GAINS-based model and IPCC-derived emission factors are applied. Each emission flow is associated with one of the four sets of emission drivers: output by industries, endowment by industries, input use by industries and household consumption. In addition, emissions from land use activities (biomass burning) are estimated by land cover types. These emissions are reported separately without association with emission drivers.

*JEL classification:* C61, D57, D58, Q54, Q56.

*Keywords:* GTAP; air pollution; Computable general equilibrium.

# Contents

# 1. Introduction

In recent years, a number of studies have contributed to the assessment of air pollution-related externalities both at regional and global scales. According to the Global Burden of Disease study, in 2015 ambient air pollution caused 4.2 million deaths and 103.1 million disability-adjusted life-years, making it the fifth-ranked global risk factor (Cohen et al., 2017). In terms of the welfare costs of mortality and illnesses associated with outdoor air pollution, global estimates range between 2.7 and 3.2 trillion USD for 2015 (Coady et al., 2015; OECD, 2016). This is equivalent to 40% of world health expenditures and is 10 times higher than global investment in renewable energy (WB, 2017; FS-UNEP/BNEF, 2017).

With such a high magnitude of air pollution-related externalities, implementing more stringent environmental policies (e.g. emission taxation or energy subsidies elimination) may result in significant co-benefits (Saari et al., 2015; Chepeliev and van der Mensbrugghe, 2017). While $CO_2$ and non-$CO_2$ GHG emissions are usually well represented in most global economic databases, air pollution flows in many cases are not included.

One of the reasons behind this situation is that global air pollution processes and related health impacts are often analyzed using specialized models (e.g. GAINS model (IIASA, 2017)), which provide detailed spatial coverage. Linking separate models of air pollution and the global economy may lead to a roughly consistent approach for global environmental policies assessment, but it is not the most straightforward and efficient approach. Thus, the purpose of this document is to describe the methodology used to produce an air pollution dataset consistent with the Global Trade Analysis Project (GTAP) Data Base (Hertel, 1997), one of the most widely used databases for global economic analyses.

The air pollution dataset constructed here is consistent with the GTAP 10a Data Base (Aguiar et al., 2019), which includes data for four benchmark years: 2004, 2007, 2011 and 2014. This effort complements the GTAP non-$CO_2$ greenhouse gas (GHG) emissions database (see Chepeliev (2020) for the most recent documentation) and $CO_2$ emissions data, which is integrated to the GTAP Data Base (Aguiar et al., 2019).

In this document, we develop the dataset that reports emissions for nine substances, 141 regions and 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 emission 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 types, based on the volumes of burned biomass (FAO, 2020) and emission factors. These emissions are reported separately without association with emission drivers. Despite some limitations, including the need to introduce assumptions on emissions mapping to users and drivers, the current approach provides a straightforward way of producing a GTAP-consistent air pollution database based on the standardized emission estimation approach.

The rest of the document is organized as follows. Section 2 provides a discussion of air pollution data sources and describes a general approach to the input data preprocessing. Section 3 discusses an approach used to map EDGAR-sourced air pollution flows to the GTAP-based emission drivers and sources, as well as estimates of the land use (biomass burning) emissions. Section 4 provides an overview of the constructed database. Section 5 discusses comparisons of EDGAR emissions with other available data sources. Finally, Section 6 concludes.

## 2. Air pollution data choice and pre-processing

Several sources for the global air pollution data are available, which can be used either separately or combined. In our effort to construct the GTAP-consistent air pollution dataset, we are imposing several criterions on the source data. First, we are aiming for a global dataset with (at least) country-level coverage, based on a standardized methodology and with the availability of regular releases over time. Second, the database should distinguish sources of air pollution, which can be further linked to economic activities.

Considering the aforementioned criteria, in this report we are using the EDGAR Version 5.0 database as a main source of air pollution data (Crippa et al., 2020). The EDGAR database provides particulate air pollutants emission by 37 emission sources (Appendix A) and 229 countries[2] (Crippa et al., 2020), covering the 1970-2015 timespan. Emissions for nine substances 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 ($SO_2$).[3]

Available emissions' disaggregation level allows us to develop an acceptable level of mapping to the GTAP sectors and corresponding sources (e.g. intermediate inputs, output, endowments, etc.), as it will be discussed in the next section of the report.

Several other data sources were also considered as an alternative/additional in the preparation of air pollution dataset within this report. The GAINS model (IIASA, 2017) provides emissions data for five substances ($NH_3$, $NO_x$, PM, $SO_2$ and VOCs), which is available by sector and fuels/activities. Data is provided by regions/countries in 5-year time steps, starting from 2005. While this dataset also has global coverage and, in some cases, enables more accurate mapping to GTAP sectors/activities, benefits from the higher disaggregation of emission sources cannot be fully utilized due to the differences in GTAP Data Base and GAINS model sectoral classifications. Furthermore, data are represented in 5-year steps, which do not match the GTAP 10 Data Base reference years. Compared to the EDGAR database, GAINS also reports lower number of air pollutants.

---

[2] 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.

[3] 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 biogenic flows, while in EDGAR v4.3.1 (Crippa et al., 2016) NMVOC emissions were split into short and long cycle carbon.

GAINS data, however, can be used to improve the allocation of 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 air pollutants ($SO_2$, $NO_x$ and PM2.5) to the corresponding fossil fuels use in the GTAP Data Base.

An alternative source for the air pollution data is available from the United Nation Food and Agriculture Organization (FAO), which provides a dataset with emissions for the agricultural-related activities (FAO, 2017). But, unlike the GHG emissions, which are covered in detail by FAOSTAT (Chepeliev, 2020), air pollution data are reported only in the form of ammonia ($NH_3$) emission shares from agriculture. Therefore, the FAO emissions dataset is not relevant for the purpose of this report. 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 types and emission factors to estimates emissions from land use activities, as discussed in the next section.

Another possible source of air pollution data is represented by WHO's Global Burden of Disease Study (Cohen et al., 2017), with the latest available data year 2015. While providing a detailed analysis of air pollution related diseases, this data source focuses mainly on the actual estimates of the ambient air pollution levels in selected countries and cities. Thus, it does not link emissions to the sources.

Also, there is a database on greenhouse gas emission factors (IPCC-EFDB) developed by the Intergovernmental Panel on Climate Change (IPCC, 2017) that 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 emission redistribution between drivers and sources, which is discussed in more detail in the next section.

## 3. Air pollution data mapping to the GTAP Data Base

This section provides a description of the approach used to link the EDGAR-based air pollution data with the GTAP 10 Data Base. In this effort, in line with Irfanoglu and van der Mensbrugghe (2015), we associate each pollution flow with one of the four sets of emission sources: output by industries, endowment by industries, input use by industries and input use by households. To provide a more accurate allocation of emissions between different types of fossil fuels consumption by industries and households we use GAINS-based emission factors, reported in Coady et al (2015), as well as IPCC-sourced emission factors provided in IPCC (2017). Figure 1 provides an overview of the dataset construction process.

The EDGAR v4.3.2 database reports PM2.5 emissions from fossil fuels (PM2.5f) and biogenic (PM2.5b) sources (Crippa et al., 2018). We use these data to provide a more consistent mapping of PM2.5 emissions reported in EDGAR v5.0 to the GTAP emission drivers. As the GTAP energy database (McDougall and Lee, 2006) 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 EDGAR v5.0 are first split into bio and fossil flows, using country and IPCC category-specific shares from the EDGAR v4.3.2. They are then mapped to the emission drivers, following approach discussed in sections 3.1-3.3 and aggregated to the single PM 2.5 category in the final database.

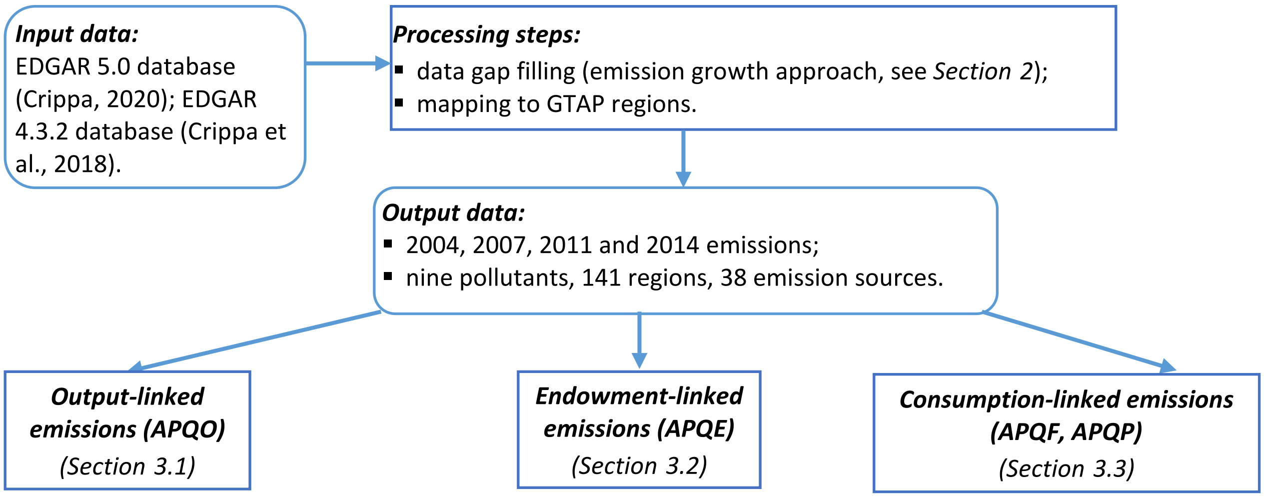


**Figure 1. GTAP air pollution database construction process**

*Source:* Author.

*Note:* This Figure excludes treatment of the land use emissions (discussed in section 3.4).

## 3.1. Air pollution 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 defined mapping between IPCC categories and GTAP emission sources, as well as mapping between IPCC categories and GTAP emission drivers, output-associated emissions (APQO) are estimated according to the following formula:

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

where $t$ is the set of years (2004, 2007, 2011 and 2014); $e$ is the set of 10 air pollutants; $k$, $i$ represent the 65 GTAP sectors; $r$ represents the 141 GTAP regions; $c$ is the set of IPCC emission categories. $ValRedist$ identifies cases with emissions redistributed proportionally to GTAP values[4] (such categories are indicated by # in the Appendixes B and C). *SecMap* provides mapping between IPCC categories and GTAP emission sources, while *DriveMap* provides mapping between IPCC

[4] We divide all IPCC categories into IPCC categories with emissions redistributed proportionally to GTAP values (value of output, endowment or consumption) and 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.

categories and GTAP emission drivers. *EmiReg* represents EDGAR-sourced emissions in gigagrams (Gg)[5] and *ValOutpt* provides value of output in million USD.

## 3.2. Air pollution associated with endowment by industries

Endowment sources account for the smallest share of pollution in all but the case of ammonia ($CH_3$) emissions. All endowment-driven IPCC pollution categories are redistributed between drivers and sectors proportionally to GTAP value flows (Appendix B), which is similar to the output-driven pollution:

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

where *m, j* are defined over the set of endowment drivers (in our case, land and capital), used for emission reallocation; *Costs* coefficient represents costs structure in million USD.

## 3.3. Air pollution associated with consumption

Consumption-related pollution reallocation is treated in two ways. In the case of pollution linked to the consumption of chemical products (IPCC codes 3A, 3B, 3C, 3D, 4D1 and 4D4) the treatment is similar to the endowment and output driven pollution, both for firms (APQF) and households (APQP):

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

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

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

where *"HHs"* label identifies households.

Different treatment is applied to the IPCC categories associated with fossil fuels combustion (IPCC categories without "#" sign in Appendix B). Figure 2 provides and overview to the general approach to fuel combustion-related emissions redistribution.

[5] 1 Gg equals 1000 metric tons.

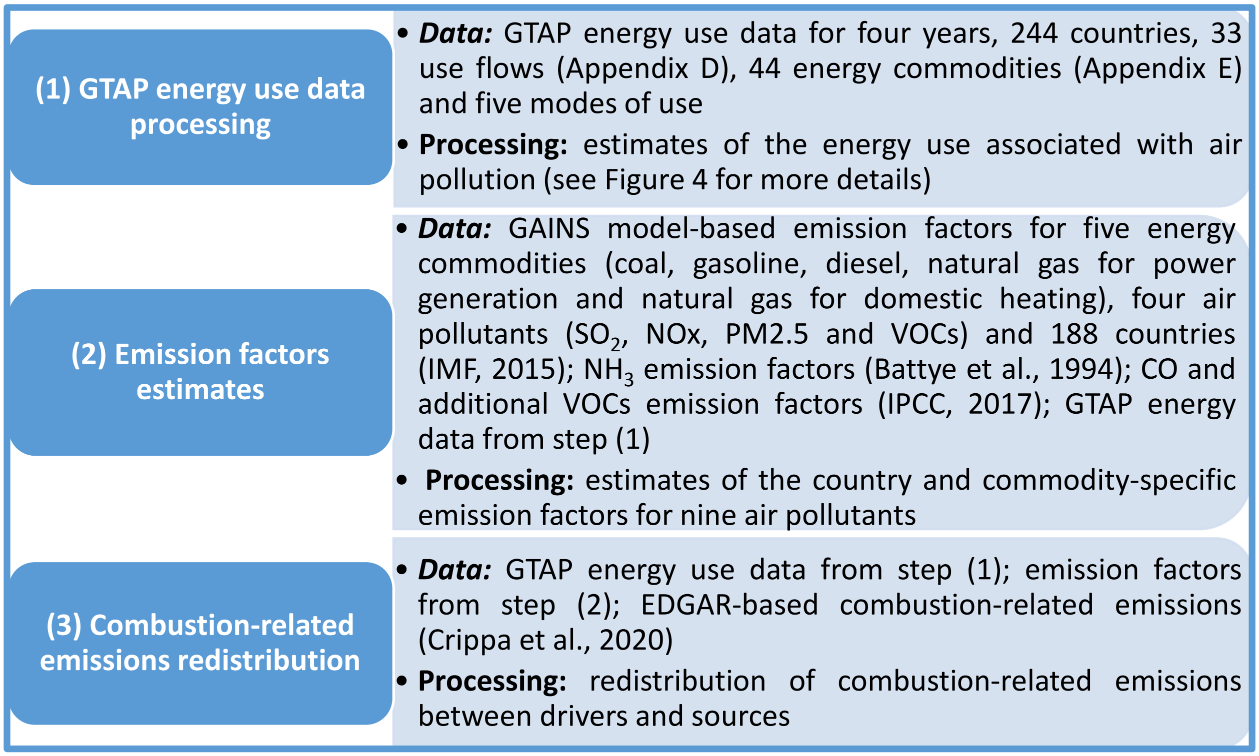


**Figure 2. Steps to redistribute fuel combustion-related emissions**
*Source:* Author.

In the case of combustion-related emissions, in the first step, we estimate energy use associated with air pollution. 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 energy that goes to transformation or exports, 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 for fuel combustion-related emissions.

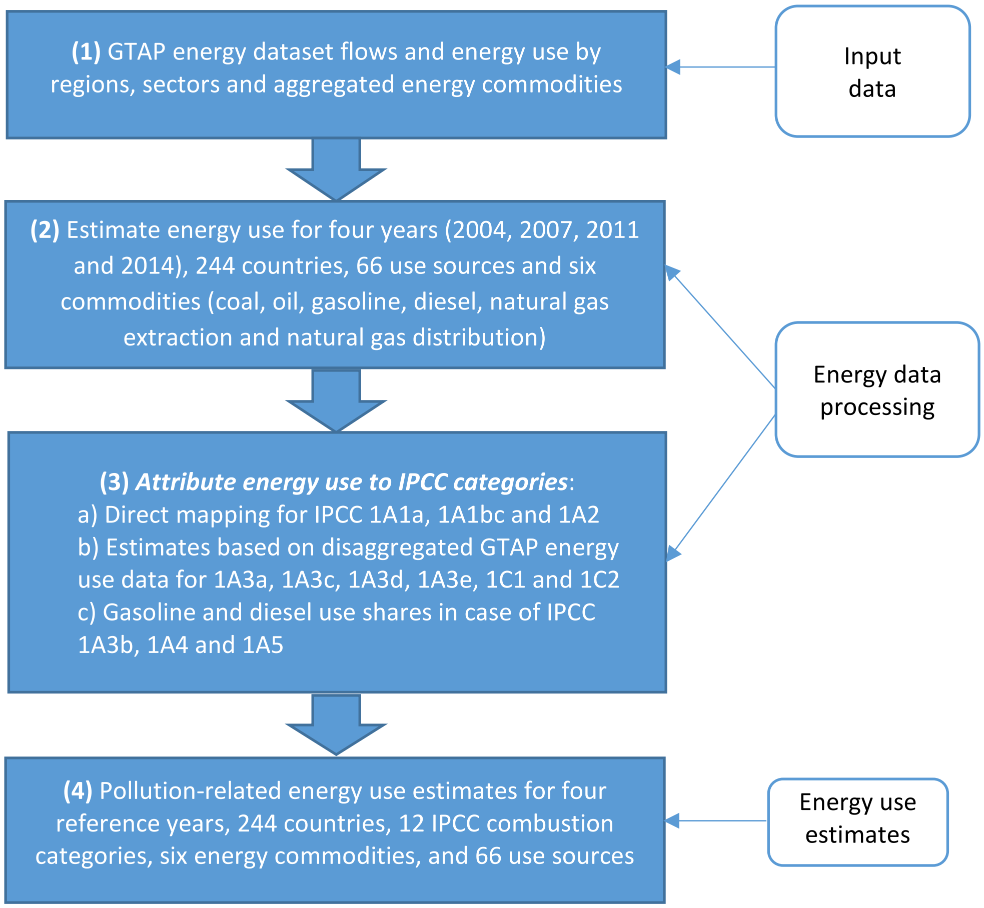


**Figure 3. GTAP energy data processing for fuel combustion-related emission estimates**
*Source:* Author.

Output files of the GTAP 10 Data Base build ("gsdvole.har") provide energy use data at a more aggregated regional and energy commodity level than required for the air pollution database development, therefore we apply additional disaggregation. This is the case for petroleum products, which are reported in aggregate in the "gsdvole.har", while available emission factors are differentiated for gasoline and diesel. We also need energy use data at a country level. To implement this, we use the GTAP energy dataset (EDS) (McDougall and Lee, 2006) with corresponding flows reported in the GTAP Data Base energy module (IEA, 2015a; 2015b). EDS 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 10 sectors and households) and six commodities (coal, oil, gasoline, diesel, natural gas extraction and natural gas distribution).

Using the developed mappings between IPCC emission sources, emission drivers and GTAP use sources (Appendix B), we allocate estimated energy use flows to the IPCC categories. In the case of IPCC categories 1A1a, 1A1bc and 1A2 we assume that EDGAR-based emissions are redistributed based on all energy use volumes and one-to-many or one-to-one mapping from IPCC codes to GTAP use categories is applied. For instance, in the case of coal use in public electricity and heat production (IPCC code 1A1a) we assume that emissions are redistributed (in this case only between drivers, as 1A1a is mapped to one GTAP sector – "ely") based on coal use data.

In the case of transportation activities – domestic aviation (1A3a), road transportation (1A3b), rail transportation (1A3c), inland navigation (1A3d), other transportation (1A3e), international aviation (1C1) and international navigation (1C2) – there is no available one-to-many or one-to-one mapping from IPCC to GTAP use categories. For instance, GTAP's other transportation sector (otp) includes rail (IPCC code 1A3c), road (1A3b) and other (1A3e) transportation IPCC categories (Appendix B). Similarly, air transportation (atp) includes both domestic (IPCC code 1A3a) and international (1C1) aviation. To estimate energy use flows for such categories we use EDS data. The list of corresponding IPCC categories and mapping to EDS commodities are provided in Appendix F.

Road transportation IPCC category (1A3b) is mapped to "otp" and households (Appendix B). To provide more consistent reallocation of emission flows, we assume that while all gasoline is associated with road transportation activities by households, 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 a total national diesel consumption. For instance, if country A consumes 100 tons of oil equivalent (toe) of diesel fuel of which 30 toe (or 30%) is consumed by road transportation activity, then we assume that in the case of households the share of diesel used for road transportation equals 30%, while the remaining 70% is used for other purposes (e.g. heating).

Finally, in the case of households under residential and other sectors category (IPCC code 1A4), we assume that no emissions are associated with gasoline use (as gasoline-related emissions are attributed to road transportation activities). The share of diesel associated with 1A4 emissions by households equals "1" less the share of diesel associated with road transportation use (this would be 0.7 in case of the example above). This step finalizes GTAP energy data processing (Figure 3) for combustion-related emission estimates.

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

The IMF energy subsidies database (IMF, 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). We first estimate world weighted average emission factors for five energy commodities and four air pollutants to gap-fill the country cases with unavailable data. As the weights for world average emission factors, we use energy data flows estimated by Step 1 (Figure 3). Emission factors for natural gas for domestic heating are applied to natural gas use by households. In the case of natural gas use by industrial users and commercial consumers we apply emission factors for natural gas use in power generation.

We further map four air pollutants from IMF database (IMF, 2015) to seven air pollutants reported in the EDGAR dataset. The corresponding mapping is provided in Appendix G. Although this assumption is somewhat simplistic, we find it an appropriate solution to fully utilize the available emission factors data. It may be reconsidered in the future upon availability of additional data.

In the case of emission factors for ammonia ($NH_3$), we use data from Battye et al. (1994) and assume these factors to be uniform across countries. For emission factors conversion to uniform units (kt/PJ) we use data on the density of corresponding fuels (JRC, 2007; Unitrove, 2017). The energy content of fuels is sourced from NER (2017). In the case of natural gas, we use emission factors for utility and industrial boilers for all sectors but households; for residential users we apply 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 14 IPCC categories (Appendix H). Out of 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 emission drivers, out of 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 emission redistribution (Appendix I). IPCC-based estimation of the CO emission factors finalizes Step 2 of the emission redistribution process (Figure 3). As the IMF energy subsidies database (IMF, 2015) does not provide VOCs emission factors for natural gas and coal combustion, we use IPCC values to gap fill these data.

We do not map emission factors related to biomass combustion, as in the GTAP energy dataset (McDougall and Lee, 2006) all energy flows associated with biomass or biofuel use are discarded from the construction process. We use corresponding value flows to redistribute biogenic PM2.5 emissions (Appendix C).

To assist with combustion-related emissions allocation, we estimate emission weights multiplying combustion-related energy use by corresponding emission factors to derive EFEMIREG values. With processed energy use data and estimated emission factors, we move to 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 pollution categories in the IPCC emission factors database associated with fossil fuels 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 pollution; $s$, $v$ correspond to emission sources.

International aviation and navigation emissions are redistributed between countries based on the value of exports reported in GTAP 10a for air transport ("atp") and water transport ("wtp") respectively, excluding exports of travelers' expenditures. These emissions are further mapped to drivers and users and added to the consumption-related emissions.

After this step, we have redistributed over 99.9% emissions reported in the EDGAR database. However, as was identified, there are some cases (less than 0.1% of global air pollution) 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 this mapping.

Finally, redistributed emissions from fossil fuel combustion (ENCOMBEMI) are mapped to the emissions associated with 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 constructed database with such estimates, we use FAO-reported volumes of biomass burning by land cover types and emission factors compiled from different sources. Figure K.1 (Appendix K) provides an overview of biomass burned (dry matter) by land cover types (FAO, 2020). Volumes of the burned biomass have been declining between 2004 and 2011, but increase in 2014, reaching 1704 million tons. In 2014, organic soils accounted for around 41% of the total volume of biomass burned followed by other forest category (31%) and humid tropical forests (28%).

Table K.1 (Appendix K) provides assumptions of emission factors by land cover types. These emission factors are mainly based Akagi et al. (2011) and are complemented by estimates from Yokelson et al. (2013) and Hu et al. (2018). As literature suggests (e.g. Akagi et al., 2011), there are large uncertainties regarding adopted emission factors, so implied estimates of land use-related air pollution should be interpreted with caution.

Estimates suggest that in the case of all pollutants, over the analyzed time horizon, 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 decreased by 20%, but their level has increase by around 16% between 2011 and 2014. On average, the share of non-GHG emissions from forests and organic soils burning is estimated to be around 25.4% of total non-GHG emissions.[6] The share of non-GHG emissions from forests and soils burning largely varies by pollutants. For instance, in the case of OC, PM10 and PM2.5, this category contributed over 40% of total non-GHG emissions, while in the case of $NO_x$ and $SO_2$ the share is below 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. 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.

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

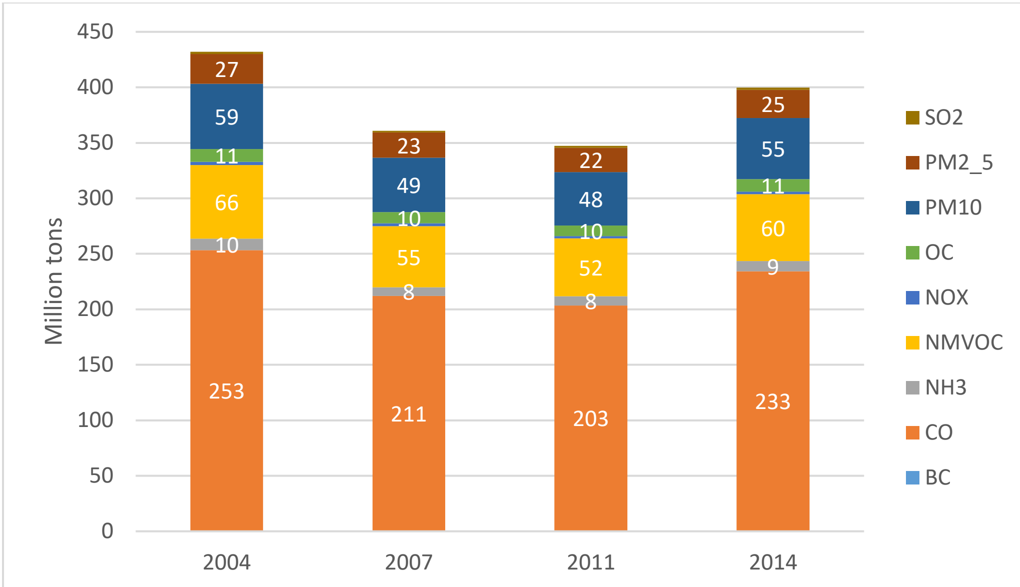


**Figure 4. Global non-GHG emissions from forests and organic soils burning**
*Source:* Estimated by author based on FAO (2020), Akagi et al. (2011), Yokelson et al. (2013) and Hu et al. (2018).

## 4. Overview of the GTAP 10a air pollution 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 forests and organic soils burning. In terms of changes over time, global air pollution has been constantly increasing, as over the 2004-2014 timeframe emission volumes has been growing for all air pollutants (Figure 5). The highest growth rates are observed for the PM2.5 and BC (on average 2.1% per year), followed by PM10 emissions (1.9% per year) and OC (1.5% per year).

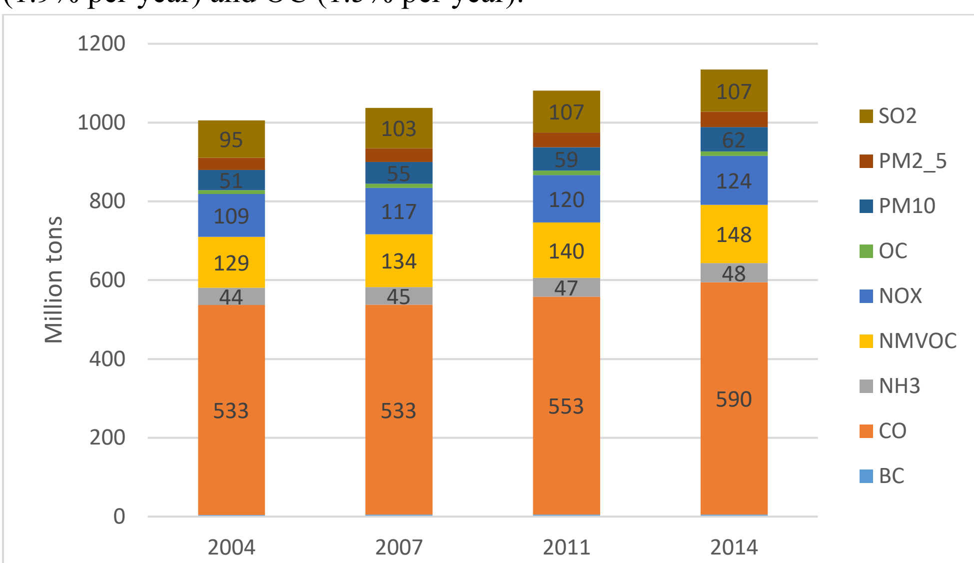


**Figure 5. Global non-GHG emissions by GTAP 10a reference years and pollutants**
*Source:* Estimated by author based on EDGAR v5.0 database (Crippa et al., 2020) and GTAP 10a air pollution database.
*Note:* Emissions from forests and organic soils are not reported on this figure.

At the global level, consumption is the most common driver of pollution (Figure 6). In the case of all nine 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, but $NH_3$. In the latter case, endowment accounts for almost 38% of pollution volumes, as emissions are produced by cattle.

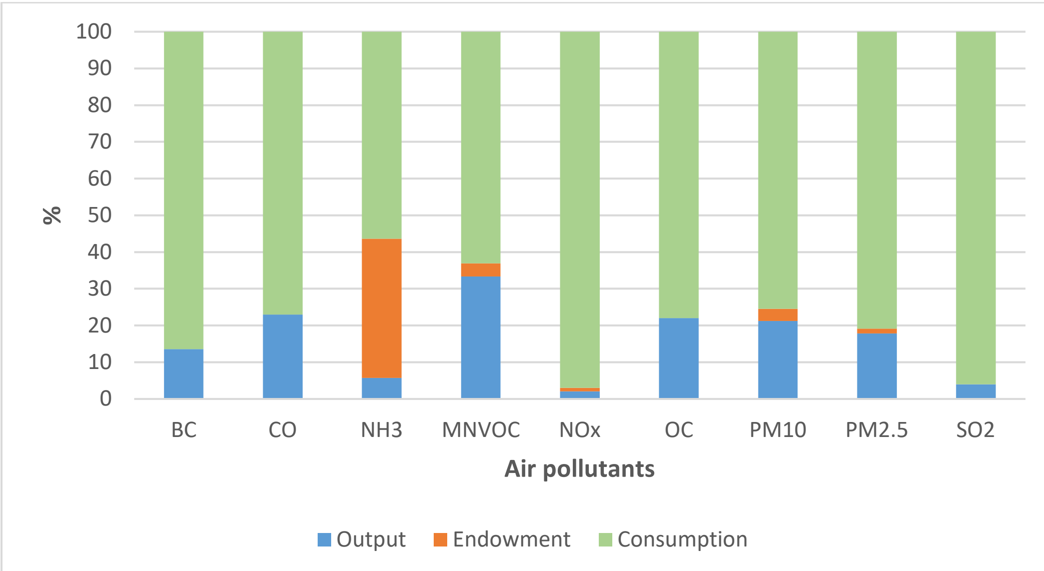


**Figure 6. Global average distribution of air pollutants by sources (2004, 2007, 2011 and 2014 weighted average)**

*Source:* Author's estimates based on EDGAR v5.0 database (Crippa et al., 2020) and GTAP 10a air pollution database.
*Note:* Emissions from forests and organic soils are not reported on this figure.

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 key contributors, accounting for at least 21% of all emissions (Figure 7). Electricity generation activity is the largest contributor in the case of two pollutants ($NO_x$, and $SO_2$). Electricity contribution reaches almost 46% in the case of $SO_2$ emissions. At the global level, contribution of the top five key emitters ranges between 52% (for BC and OC) 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.

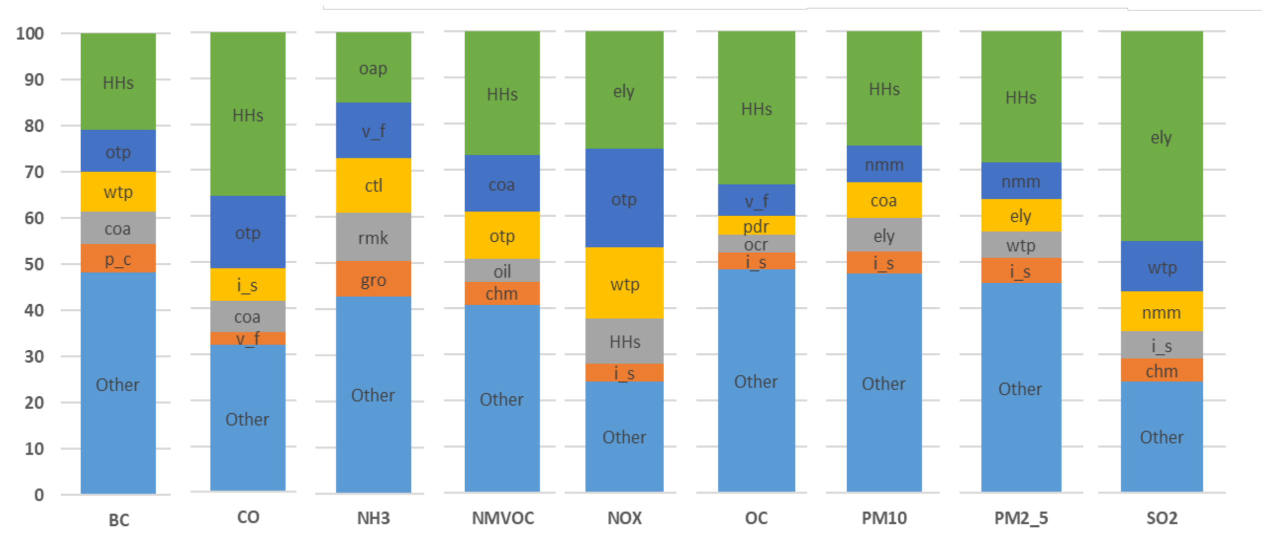


**Figure 7. Distribution of global emissions by users, % (2004, 2007, 2011 and 2014 weighted average)**

*Source:* Author's estimates based on GTAP 10a air pollution database.

*Note:* Five top contributors are explicitly identified for each pollutant, rest users are included to the "Other" category. Sectoral labels follow definitions provided in Aguiar et al. (2019). "HHs" stands for households. Emissions from forests and organic soils are not reported on this figure.

## 5. Comparison of EDGAR v5.0 with other emissions data sources

To explore the consistency of the EDGAR-reported air pollution data, we have developed comparisons with several other available data sources at the global level. These include Representative Concentration Pathways (RCPs) database (van Vuuren et al., 2011) and air pollution accounts developed in Lamarque et al. (2010). Considering that the latest data year reported in Lamarque et al. (2010) is 2000, this year was used to provide data comparisons. It should be also 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.

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 case of some pollutants (e.g. OC) forest and grassland burning activities could contribute over 60% of all emissions (Figure 7). Decomposition of the RCP emissions into forest burning, grassland burning and other sources, explains initially observed large discrepancies between EDGAR and the RCPs (Figure 7). Once emissions from forest and organic soils burning are taken into account, initially observed difference are significantly reduced. Large uncertainties around biomass burning emission factors (Akagi et al., 2011) is one of the key contributors to the observed differences in emissions between different sources.

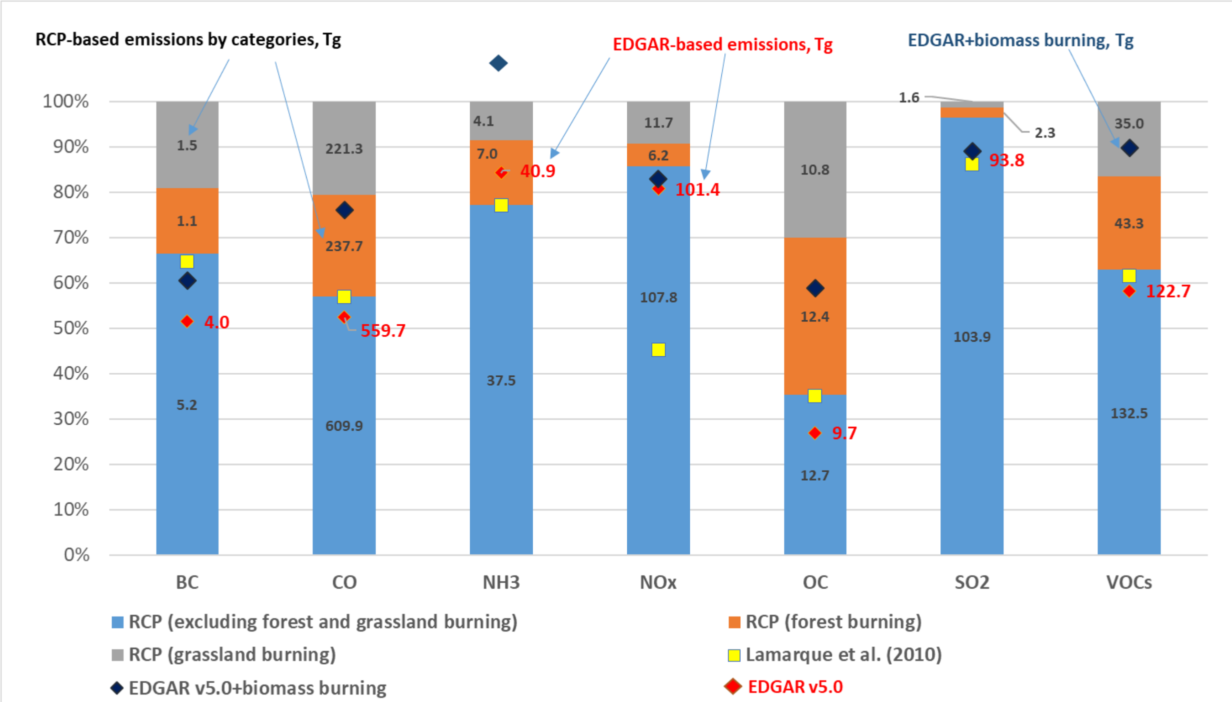


**Figure 7. Comparison of EDGAR v5.0 global emissions in 2000 with other data sources**

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

*Note:* 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; 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 emission (from the year 2004) are added to the EDGAR v5.0 emission 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.

It should be noted that the revision of reported emissions has been introduced between EDGAR v4.3.2 (Crippa et al., 2018) and EDGAR 5.0 (Crippa et al., 2020) databases. 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 up to 13.5% in the case of NMVOC (Figure 8). Revision of the BC emissions has resulted in their increase by around 9.1% for 2000.

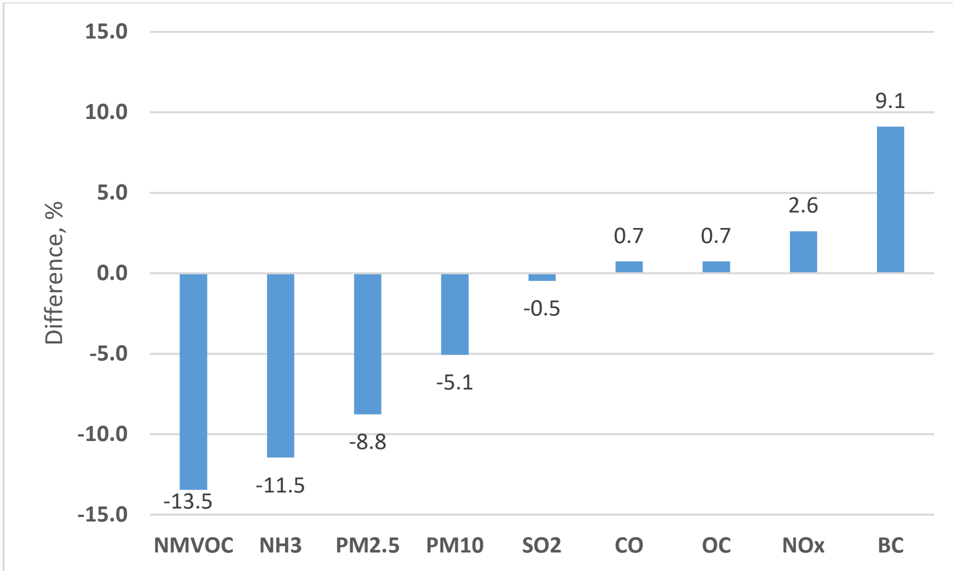


**Figure 8. Difference between global emissions reported in EDGAR v4.3.2 and EDGAR v5.0 for 2000 (v5.0 relative to v4.3.2 levels, i.e. negative numbers indicate that v5.0 emissions are lower than in v4.3.2)**

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

## 6. Conclusions

In this document, we have developed a methodology to construct an air pollution database using EDGAR-based emissions data, GTAP energy use data, and emission factors sourced from several sources. Following this methodology, we have produced an air pollution dataset consistent with the GTAP 10a Data Base, which includes data for nine air pollutants, four reference years (2004, 2007, 2011 and 2014) and 141 regions. While this effort is aimed at providing a valid step towards incorporation of the environmental accounts to the input-output and CGE modelling frameworks, several important limitations and potential improvements should be discussed.

First, in the process of associating emission sources with GTAP users and drivers, specific mapping assumptions have been introduced. Though such mapping has 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 the additionally available 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 is 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 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 constructed GTAP air pollution database with emissions from forests and organic soils burning, improving the representation of global non-GHG emissions. At the same time, in the constructed database, these emissions are reported separately, i.e. are not linked to the emission drivers. Development of the possible treatment of these emissions in model simulations could be one possible improvement of the constructed database.

Finally, in terms modelling application, the developed dataset provides links between emission flows, drivers and activities. Therefore, changes in the level of economic activities (output, consumption, endowment use) resulting from specific policy simulations could be directly linked to changes in emission volumes. At the same time, the constructed 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 policies. Development of the marginal abatement cost curves (MACCs) for the reported air pollutants could be an important addition to the constructed dataset.

# References


Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., and van der Mensbrugghe, D. 2019. The GTAP Data Base: Version 10. Journal of Global Economic Analysis, Vol. 4, No. 1. https://www.gtap.agecon.purdue.edu/resources/jgea/ojs/index.php/jgea/article/view/77.

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O. 2011. Emission factors for open and domestic biomass burning for use in atmospheric models, Atmos. Chem. Phys., 11, 4039–4072, https://doi.org/10.5194/acp-11-4039-2011.

Battye, R., Battye, C., Overcash, C. and Fudge, S. 1994. Development and selection of ammonia emission factors. U.S. Environmental protection agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100ERTR.PDF?Dockey=P100ERTR.PDF

Chepeliev, M. 2020. Development of the Non-$CO_2$ GHG Emissions Database for the GTAP Data Base Version 10A. Research Memorandum No. 32. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5993

Chepeliev, M. and van der Mensbrugghe, D. 2017. Global energy subsidies reform: inclusive approaches to welfare assessment. Presented at the 20th Annual Conference on Global Economic Analysis, West Lafayette, USA. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5299

Coady, D., Parry, I., Sears L., Shang, B., 2015. How Large are Global Energy Subsidies? IMF Working Paper WP/15/105. http://www.imf.org/external/pubs/cat/longres.aspx?sk=42940.0

Cohen, A., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., et al. 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Disease study 2015. *The Lancet*. 2017, April.

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., Janssens-Maenhout, G.: High resolution temporal profiles in the Emissions Database for Global Atmospheric Research, Nature Scientific Data, 2020, in press.

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., van Aardenne, J. A., Monni, S., Doering, U., Olivier, J. G. J., Pagliari, V., and Janssens-Maenhout, G. 2018. Gridded Emissions of Air Pollutants for the period 1970–2012 within EDGAR v4.3.2, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-31

Crippa, M., Janssens-Maenhout, G., Dentener, F., Guizzardi, D., Sindelarova, K., Muntean, M., Van Dingenen, R., and Granier, C.: Forty years of improvements in European air quality: regional policy-industry interactions with global impacts, Atmos. Chem. Phys., 16, 3825–3841, https://doi.org/10.5194/acp-16-3825-2016, 2016.

European Environmental Agency. 2013. Status of black carbon monitoring in ambient air in Europe. Technical report No 18/2013. https://www.eea.europa.eu/publications/status-of-black-carbon-monitoring/

Eurostat. 2015. Manual for air emissions accounts. http://ec.europa.eu/eurostat/documents/3859598/7077248/KS-GQ-15-009-EN-N.pdf/ce75a7d2-4f3a-4f04-a4b1-747a6614eeb3

Food and Agricultural Organization of the United Nations (FAO). 2020. FAOSTAT. http://www.fao.org/faostat/en/#home

Frankfurt School-UNEP Center/BNEF (FS-UNEP/BNEF). 2017. Global Trends in Renewable Energy Investment 2017. http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf

Hertel, T.W., editor. 1997. Global Trade Analysis: Modelling and Applications, Cambridge University Press.

Houghton, J.T. et al. (eds). 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (UK Meteorological Office, Bracknell, 1997). http://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch1ri.pdf

Hu, Y. Q., Fernandez-Anez, N., Smith, T. E. L., and Rein, G. 2018. Review of emissions from smouldering peat fires and their contribution to regional haze episodes, Int. J. Wildland Fire, 27, 293–312, https://doi.org/10.1071/wf17084, 2018.

International Energy Agency (IEA). 2015a. Energy Balances of OECD Countries (2015 edition). Database. International Energy Agency. Paris, France. https://www.oecd-ilibrary.org/energy/energy-balances-of-oecd-countries-2015_energy_bal_oecd-2015-en.

International Energy Agency (IEA). 2015b. "Energy Balances of Non-OECD Countries (2015 edition)." Database. International Energy Agency. Paris, France. https://www.oecd-ilibrary.org/energy/energy-balances-of-non-oecd-countries_19962843-en.

Intergovernmental Panel on Climate Change (IPCC). 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 4. Fugitive Emissions. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/2_Volume2/19R_V2_4_Ch04_Fugitive_Emissions.pdf

Intergovernmental Panel on Climate Change (IPCC). 2017. Database on greenhouse gas emission factors (IPCC-EFDB). November 2017. http://www.ipcc-nggip.iges.or.jp/EFDB/main.php

International Energy Agency (IEA). 2017. World Energy Balances: 2017 Preliminary Edition. Database Documentation. http://wds.iea.org/wds/pdf/OECDBAL_Documentation.pdf

International Institute for Applied System Analysis (IIASA). 2017. The GAINS model. http://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html

Irfanoglu, Z.B., van der Mensbrugghe, D. 2015. Development of the version 9 non-$CO_2$ GHG emissions database. Documentation accompanying dataset. https://www.gtap.agecon.purdue.edu/resources/download/7813.pdf

JRC. 2007. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context TANK-to-WHEELS Report; Version 2c, March 2007. https://web.archive.org/web/20110720162258/http://ies.jrc.ec.europa.eu/uploads/media/TTW_Report_010307.pdf

Lamarque, J.F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne, J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K., Van Vuuren, D.P., 2010. Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. Atmospheric Chemistry and Physics Discussions 10, 4963-5019. doi:10.5194/acp10-7017-2010.

McDougall, R. A. and Lee, H.-L. 2006. GTAP 6 Data Base: Chapter 17 - An Energy Data Base for GTAP In Dimaranan, Betina V., Editor (2006). *Global Trade, Assistance, and Production: The GTAP 6 Data Base*, Center for Global Trade Analysis, Purdue University. https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1951

New Energy Research (NER). 2017. Energy content of fuels. http://bxhorn.com/energy-content-of-fuels/

Organisation for Economic Co-operation and Development (OECD), 2016. The economic consequences of outdoor air pollution. https://www.oecd.org/environment/indicators-modelling-outlooks/Policy-Highlights-Economic-consequences-of-outdoor-air-pollution-web.pdf

Saari, R.K., Selin, N.E., Rausch, S. and Thompson T.M., 2015. A self-consistent method to assess air quality co-benefits from U.S. climate policies. Journal of the Air & Waste Management Association, 65:1, 74-89, DOI: http://dx.doi.org/10.1080/10962247.2014.959139

The World Bank (WB). 2017. Health expenditure, total (% of GDP). https://data.worldbank.org/indicator/SH.XPD.TOTL.ZS

Unitrove. 2017. Natural gas density calculator. http://www.unitrove.com/engineering/tools/gas/natural-gas-density

van Vuuren, D.P., Edmonds, J., Kainuma, M. *et al.* 2011. The representative concentration pathways: an overview. *Climatic Change* **109,** 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

Yokelson, R.J., Burling, I.R., Gilman, J.B., Warneke, C., Stockwell, C.E., de Gouw, J., Akagi, S.K., Urbanski, S.P., Veres, P., Roberts, J.M., Kuster, W.C., Reardon, J.,Griffith, D.W.T., Johnson, T.J., Hosseini, S., Miller, J.W., Cocker III, D.R., Jung, H., Weise, D.R. 2013.

Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires. Atmos. Chem. Phys. 13, 89–116.

## Appendix A. Global emissions distribution by IPCC categories and pollution substances in the EDGAR 5.0 database[7]

| IPCC code | Air pollution 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 |

[7] 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 pollution source description | Emission substances (2004-2014 average shares, %) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ***BC*** | ***CO*** | $NH_3$ | ***NMVOC*** | $NO_x$ | ***OC*** | ***PM10*** | ***PM2.5*** | $SO_2$ |
| 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 |
| 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** |

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

*Note:* Cases with shares greater than 10% are highlighted bold.

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

| No. | IPCC 1996 code | Air pollution source description | Emission driver | ISIC Rev. 3 code[8] | Comments on sectoral mapping | GTAP 10 use sources[9] 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 | We map to electricity sector exclusively as heat production in GTAP is included to 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) | We exclude ISIC 40, 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) |
| 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[10] | Energy use data; emission factors (Coady et al., 2015; IPCC, 2017) |
| 6 | 1A3b_RES[#] | Road transportation (resuspension) | Output | | Emissions are linked to the road transportation only | otp | |

[8] ISIC Rev. 3.1 codes are derived from Eurostat (2015), unless otherwise noted. ISIC codes in round brackets suggest possible (non-primary) mapping.
[9] GTAP use sources include 65 sectors and households.
[10] In the case of households, 1A3B emissions are linked to the “p_c” use only.

| No. | IPCC 1996 code | Air pollution source description | Emission driver | ISIC Rev. 3 code[8] | Comments on sectoral mapping | GTAP 10 use sources[9] mapping | Source for emissions distribution |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 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, osg, edu, hht, dwe, HHs[11] | Energy use data; emission factors (Coady et al., 2015; IPCC, 2017) |
| 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 | Direct attribution |

[11] In the case of households, 1A4 emissions are linked to the use of "coa", "oil", "gas" and "gdt".

| No. | IPCC 1996 code | Air pollution source description | Emission driver | ISIC Rev. 3 code[8] | Comments on sectoral mapping | GTAP 10 use sources[9] mapping | Source for emissions distribution |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 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[12] |
| 15 | 1C2 | Memo: International navigation | Consumption (coa, oil, gas, gdt, p_c) | 61* | | wtp | Distributed by regions based on the value of exports |
| 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 ($CO_2$) | Consumption of chemical products | - | | All sectors, including HHs | Distributed proportionally to chemical products use |

[12] Fugitive emissions from international navigation are mapped to the fuel use in water transportation sector.

| No. | IPCC 1996 code | Air pollution source description | Emission driver | ISIC Rev. 3 code[8] | Comments on sectoral mapping | GTAP 10 use sources[9] mapping | Source for emissions distribution |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 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 |
| 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 | Endowment (capital) | 01 | | ctl, oap, rmk | Distributed proportionally to capital stock |
| 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 (land) | 01 | | ctl, oap, rmk | Distributed proportionally to land 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 |

| No. | IPCC 1996 code | Air pollution source description | Emission driver | ISIC Rev. 3 code[8] | Comments on sectoral mapping | GTAP 10 use sources[9] mapping | Source for emissions distribution |
|---|---|---|---|---|---|---|---|
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| 33 | 4F# | Agricultural waste burning | Output | 01 | | pdr, wht, gro, v_f, osd, c_b, pfb, ocr | Distributed proportionally to sectoral output |
| 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 | We exclude agricultural sectors and assume 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 | | We assume that fossil-fuel fires are mainly associated with coal mining and oil extraction | coa, oil | Distributed proportionally to sectoral output |

*Source:* Developed by authors.

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

## Appendix C. Mapping between EDGAR air pollution sources, PM2.5 biogenic emission drivers and GTAP sectors

| No. | IPCC 1996 code | Air pollution 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) | We map to electricity sector exclusively as heat production in GTAP is included to electricity sector | ely | Distributed proportionally to intermediate consumption |
| 2 | 1A1bc# | Other Energy Industries | Consumption (frs, lum) | We exclude ISIC 40, 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) | 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. “frs” self-consumption is excluded. Intermediate consumption of “lum” is excluded to avoid non-energy use. | pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, fsh, wtr, trd, afs, whs, cmn, ofi, ins, obs, rsa, ros, osg, edu, hht, dwe, HHs | Distributed proportionally to consumption |
| 5 | 1B1# | Fugitive emissions from solid fuels | Output | Following IPCC (2019), we identify four sources of fugitive emissions for biomass, these include emissions arising during the production of charcoal and biochar, emission during the production of wood pellets and emissions from the transformation of | chm, lum, gdt | Direct attribution |

| No. | IPCC 1996 code | Air pollution 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** |
| | | | | biomass into syngas, and, then into liquid hydrocarbons fuels. | | |
| 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 | We exclude agricultural sectors and assume 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 |

*Source:* Developed by authors.

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

## 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 Lee (2006).

# Appendix E. Concordance between GTAP energy dataset commodities and extended energy commodities sourced from IEA energy balances

| No. | GTAP EDS commodity code | EDS commodity description | Corresponding 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 excluding 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 Lee (2006).

## 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 | PipelnTransp | Pipeline transport |
| | | NonSpecTrnsp | Non-specified transport |
| 1C1 | Memo: International aviation | IntlAvBnkr | International aviation bunkers |
| 1C2 | Memo: International navigation | IntlMarBnkr | International marine bunkers |

*Source:* Authors.

## 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 | IMF (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) | IMF (2015) |
| **5** | $NO_x$ | Nitrogen oxides | $NO_x$ | IMF (2015) |
| **6** | OC | Organic carbon | PM2.5 | IMF (2015) |
| **7** | PM10 | Particulate matter 10 | PM2.5 | IMF (2015) |
| **8** | PM2.5 | Particulate matter 2.5 | PM2.5 | IMF (2015) |
| **9** | $SO_2$ | Sulfur dioxide | $SO_2$ | IMF (2015) |

*Source:* Authors.

## 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 pollution estimates

| No | IPCC database fuel code | IPCC fuel code description | Air pollution 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") |

*Source:* Based on IPCC (2017).
*Note:* * 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.

## 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

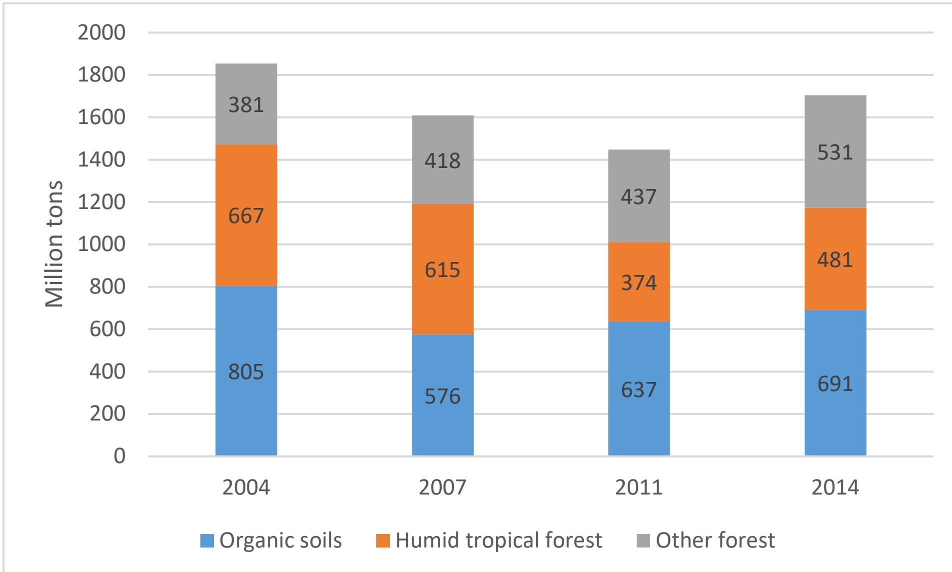


**Figure K.1. Biomass burned (dry matter) by land cover types and years, million tons**

*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* |

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

*Note:* 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). $SO_2$ 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.