Data-Informed Disaggregation and Implicit Estimation of Emissions in Other Subsectors

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1. Introduction

Greenhouse gas (GHG) emissions inventories are crucial tools for setting mitigation targets, measuring progress toward goals and for accountability within the context of national and international commitments. There are several organizations – governments, academia and commercial entities – that are involved in data collection and preparation of inventories.

Of these, one of the most important sources of GHG data are official country inventories. All countries that are parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to prepare GHG inventories as part of their commitments toward Monitoring, Reporting and Verification (MRV) for which standardized requirements have been developed (UNFCCC, 2022). Annex 1 countries are required to provide annual inventories covering emissions and removals of direct GHGs – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) – from five sectors (energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste), and for all years from the base year (or period) to two years before the inventory is due. Non-Annex 1 countries, on the other hand, have less stringent requirements and provide inventories as part of the national reports every 2-4 years and include other information such as mitigation actions, constraints and gaps, including support needed and received. As a result, these reporting requirements create a patchwork of GHG data that has varying levels of completeness, comprehensiveness, and detail.

Apart from official country inventories, several academic and research organizations also produce inventories at varying levels of granularity and recency. These inventories rely on statistics from the International Energy Agency (IEA; IEA 2022), the BP Statistical Review of World Energy (now produced by the Energy Institute; Energy Institute, 2024), the Food and Agriculture Organization's FAOSTAT database (Food and Agriculture Organisation2024), and the United Nations Statistical Division datasets (all of which rely on government data sources to some degree; UNSD/UNEP 2024). Examples of these inventories include the Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al. 2021; Crippa et al. 2024), PIK-Potsdam PRIMAP (Gütschow et al. 2021), and Global Carbon Project (Friedlingstein et al. 2022).

However, despite the existence of many global emissions inventories, several clear challenges exist for any policymaker seeking to access complete publicly available global greenhouse gas emissions estimates in practice.

The key challenges identified by Climate TRACE to accessing a complete global inventory were:

- **Geographic completeness:** Many otherwise high quality inventories informally referred to as "global" did not, upon close investigation, actually cover the entire globe. As a general rule, inventories were often relatively complete in wealthier countries, but frequently had significant gaps in the global South. EDGAR, for example, reports emissions for all sectors and countries, but sometimes has a time lag.
- **Sector completeness:** Nearly every inventory Climate TRACE was able to identify covered only certain sectors, rather than the total emissions for a geography. UNFCCC Annex 1 National Inventory Reports for example, report emissions for all sectors (but are not available in every geography and have a time lag).
- **Temporal completeness and recency:** Many existing inventories are not published every year. Most are also not published until at least 2 years after the emissions occurred. Some countries' most recent inventories–particularly the official UNFCCC inventories of non-Annex 1 countries–were as much as 10 years ago. A few exceptions exist, most notably Carbon Monitor which publishes emissions estimates only a week after the time period measured.

In addition, the lack of completeness and standardization of emissions inventories can make data harmonization and cross-validation difficult or, in some cases, impossible.

The goal of Climate TRACE is to address these challenges by providing a globally complete and comprehensive national level GHG inventory that is:

- Continually updated every year with emission values up to at least the preceding calendar year and the current year's emissions projected. In 2025, Climate TRACE GHG estimates were updated to include 2015-2025 national level emission estimates;
- Estimate emissions from all emitting subsectors with as much granularity as possible;
- Attributes all GHGs down to the emitting source/asset.

Table S3, in the supplemental section, provides a list of Climate TRACE sectors with IPCC equivalent sector coverage. Despite these continuing efforts, due to the nature of some subsectors (too many facilities, lack of existing data sources, lack of any visible satellite-derived signal), some emissions were still being estimated at the country-level only. For example, roughly 6.4% of 2015-2022 GHG emissions, or about 29 billion tonnes of carbon dioxide equivalent (CO_2e), were attributed to "*other-manufacturing*" in the 2023 (Version 3.0) release of Climate TRACE data. *Other-manufacturing* consisted of emissions from various industry and manufacturing subsectors, including from the production, creation and/or processing of electronics, lime, glass, food, wood products, and textiles, estimated at the country-level despite each of these having a unique sectoral code in the United Nations Framework Convention on Climate Change (UNFCCC; UNFCCC, 2024). Furthermore, other existing inventories also combine these subsectors, making it difficult to quantify the climate impact of these individual industries. A deeper understanding of the contribution of each of these individual industries/sectors to GHG emissions will better inform decision making at the global, country and local levels.

In order to have a complete inventory of all GHG sources in every country/ region in the world, Climate TRACE members and contributors use several measurement and estimation techniques:

1) **Machine Learning + Satellite Measurements**: These models utilize detectable signals in satellite imagery to quantify activities at a facility and then subsequently estimate emissions based on the change in these activities using machine learning algorithms (e.g. steam plumes from power plants or heat from steel plants).
2) **Statistical Modeling + Satellite Measurements**: These models utilize satellite imagery to identify and characterize emission causing sources, such as the facility type, its size, and use statistical approaches to estimate emissions (e.g. cattle operations and wastewater treatment plants).
3) **Statistical Modeling + Reported Data**: These models utilize reported data gathered from public or proprietary sources and estimate emissions using statistical models (eg. aviation emissions using the ICAO methodology or oil refining emissions using the PRELIM model).
4) **Data-informed Emissions Disaggregation**: This method estimates emissions for facilities for which very little information is available (such as their location, capacity, type of manufacturing process, production quantities, etc). It utilizes existing GHG inventories and disaggregates sectoral emissions to all the known facilities in the country which are obtained from public and other databases (e.g. textile manufacturing and food and beverage manufacturing).
5) **Implicit Estimation**: For all other sectors where facility level emission could not be estimated using any of the above 4 methods, emissions are ‘implicitly’ estimated using existing GHG inventories, subtracting out the subsector(s) that Climate TRACE estimates using methods 1-4.

Estimates from Climate TRACE members and contributors using techniques 1, 2, and 3 make up 79% of global emissions. This document describes techniques 4 and 5, where Climate TRACE uses the Intergovernmental Panel on Climate Change (IPCC) common reporting framework (IPCC 2006) along with other inventories to develop novel techniques to complement other GHG measurement methods in forming a global, comprehensive greenhouse gas inventory.

Here, we outline a process for the "Data-informed Emissions Disaggregation" technique, i.e. estimating both country- and asset-level emissions for several manufacturing subsectors originally encapsulated in *other-manufacturing* in previous Climate TRACE releases. The goal is to slim down and/or identify the unknown manufacturing subsectors lumped into *other-manufacturing*, common amongst GHG inventories. Multiple existing country-level inventories and economic datasets, as well as asset-level information from several data sources, were employed within a data-informed framework to disaggregate emissions to specific locations. This work is part of a larger effort across all Climate TRACE sectors to improve completeness of emissions at the asset and source levels, and also to increase both the granularity and accuracy of these emissions estimates. The following manufacturing subsectors were estimated using this method:

- *Glass*
- *Lime*
- *Textiles, leather, and apparel (at the asset level only)*
- *Food, beverage, and tobacco*

These subsectors together accounted for approximately 2% of global emissions in 2024.

For all other subsectors where Climate TRACE currently does not have a data-informed disaggregation estimation methodology yet due to the lack of facility-level information, emissions were implicitly estimated - technique 5 - using the Emissions Database for Global Atmospheric Research (EDGAR) and Food and Agriculture Organization of the United Nations (FAOSTAT) emissions inventories in order to provide a comprehensive emissions inventory at the country-level. The following sectors and subsectors incorporate EDGAR or FAOSTAT emissions data at the country-level:

- **Power sector:** *Other energy use*
- **Transportation sector**: *Railways; Other transportation*
- **Buildings sector:** *Other onsite fuel usage*
- **Fossil fuel operations sector:** *Other solid fuels; Other fossil fuel operations*
- **Manufacturing sector:** *Wood and wood products, Other metals, Other chemicals, Other mining and quarrying, Textiles, leather, and apparel (country-level), Other manufacturing*
- **Agriculture sector:** *Enteric fermentation - Other; Manure management - Other; Other agricultural soil emissions; Cropland fires;*
- **Waste sector:** *Biological treatment of solid waste; Incineration and open burning of waste;*
- **Fluorinated gases sector:** *Fluorinated gases*

These subsectors together accounted for approximately 19% of global emissions in 2024.

The overall approach, followed by specific methods for quantifying country-level and asset-level emissions are presented in Section 2. Section 3 outlines the results from this analysis, while in Section 4, the implications and future considerations are discussed. Furthermore, starting in November 2025, Climate TRACE is now providing emission reduction solutions (ERSs) to each sector to understand how sector mitigation strategies can be used to reduce emissions. ERS is discussed further in Section 5 below.

2. Materials and Methods

Here, we describe the two approaches, the **Data-informed Emissions Disaggregation** and **Implicit Estimation,** used to estimate emissions for the other subsectors.

2.1 Data-informed Emissions Disaggregation

2.1.1 Datasets employed

To slim down and/or identify manufacturing subsectors and to generate emissions estimates, various emissions inventories, asset location and emissions data, and economic data were employed. These datasets were then used with Climate TRACE asset-level emissions data to isolate what other types of manufacturing industries exist in "*other manufacturing"*. This includes:

- Country-level emissions quantities for each sector were taken directly or derived from the *Emissions Database for Global Atmospheric Research (EDGAR)* (EDGAR, 2023), *Community Emissions Data System (CEDS)* (Hoesly and Smith, 2024), and *United Nations Framework Convention on Climate Change (UNFCCC) Annex-I country-level emissions* (UNFCCC, 2024) datasets.
- Asset location, emissions, and other metadata were obtained from the following databases/locations: *European Pollutant Release and Transfer Register (EPRTR)* (European Environment Agency, 2023), *Israel Pollutant Release and Transfer Register (Israel PRTR)* (Israel Environmental Licensing and Risks Prevention Division, 2024), *US EPA Facility Level Information on Greenhouse gases Tool (FLIGHT)* (US EPA Office of Atmospheric Protection, 2024), *Canada Greenhouse Gas Reporting Program (Can-GHGRP)* (Government of Canada, Environment and Climate Change Canada, 2024), *Open-Supply Hub* (2024), and other government websites.
- Country-level economic data were obtained from the *Industrial Statistics Revision 4* (UNIDO, 2025), and annual lime production data were obtained from the Lime Statistics and Information (USGS, 2025). These data were used to provide an estimate of sector activity at the country and asset levels.

2.1.2 Model development

In general, the workflow for generating emissions estimates for sectors within *other-manufacturing* starts with the existing EDGAR and CEDS emissions inventories, which provide country-level emissions estimates for each gas, by 'sector' (Figure 1). While both of these inventories aim for sectoral completeness, the partitioning of the emissions into sectors varies slightly. This allows us to piece together all emissions estimates from a given sector in a logical manner using a combination of these two inventories, in addition to the UNFCCC emissions database. The specific equations for deriving individual sectors are presented in Section 2.3.1. In short, the intention was to capture all emitting sources contributing to a given facility's GHG emissions, including direct emissions, from other chemical processes, for instance, or those from associated combustion. This data-informed formulation allows us to directly disaggregate country-level sectoral emissions estimates to individual assets.

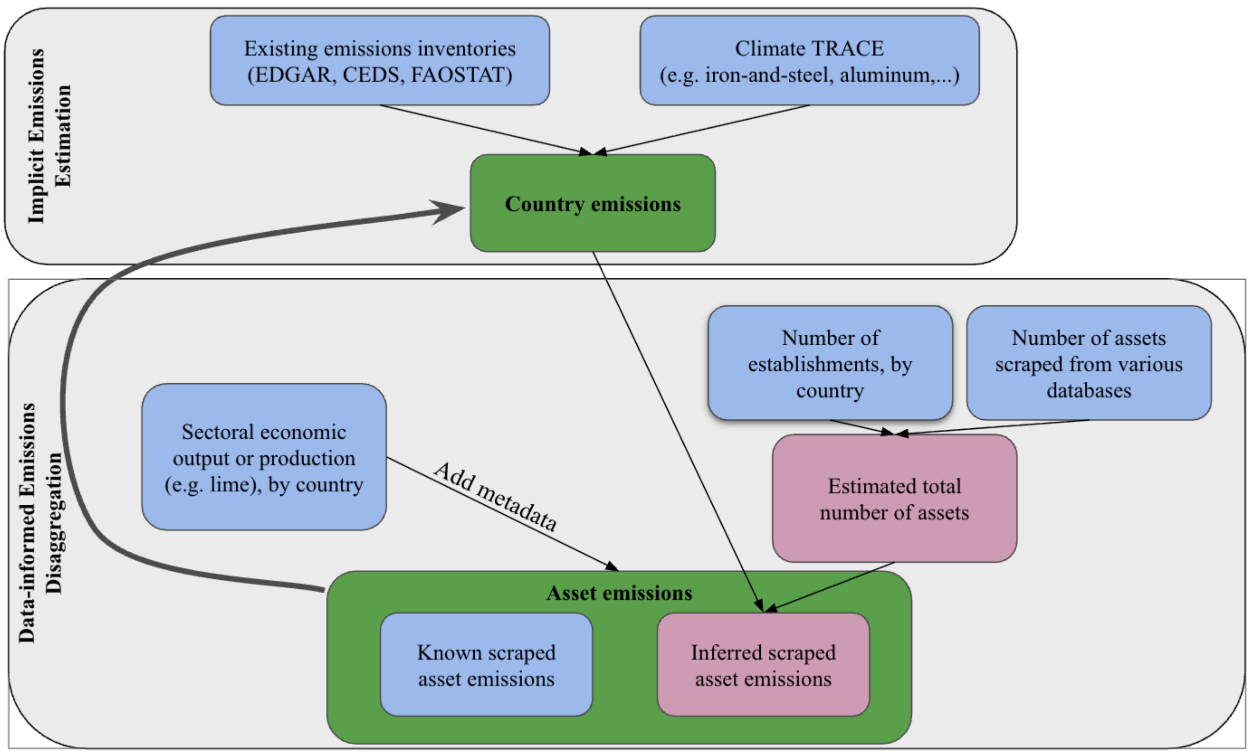

Figure 1. General process of creating country and asset-level emissions, along with associated metadata for each sector. The colors denote the type of information used in each step, with input data in blue, intermediate derived data in pink, and the final output data in green.

2.1.3 Methods

Country-level estimates exist for every sector, but only a subset contains information at the asset level. The method for estimating country-level emissions is described in Section 2.3.1, while the method for estimating asset-level emissions is described in Section 2.3.2.

2.1.3.1 Deriving country-level emissions

The following sections outline the equations used to quantify country-level emissions for the following sectors: *food, beverage, and tobacco*, *glass*, lime, and *textiles, leather, and apparel*. The CEDS or EDGAR sector naming convention is kept for clarity and other Climate TRACE sectors not described in this document but are used to derive the sectors discussed here are denoted with 'CT'. Country-level emissions from these two inventories are available through 2022, and are forward filled through the latest month of data for each release.

2.1.3.1.1 Food, beverage, and tobacco

In both EDGAR and CEDS, direct emissions from food, beverage, tobacco and wood manufacturing were categorized together, while combustion related emissions from food, beverage, and tobacco are reported separately from those from wood and wood products. Therefore we needed some way of estimating direct emissions from the subset of food, beverage, and tobacco manufacturing since Climate TRACE already accounts for wood and wood product manufacturing. The UNFCCC provides estimates of both direct (2.H.2) and indirect (1.A.2.e) emissions from food, beverage, and tobacco manufacturing for Annex I countries. Using these, we calculated a country-specific scaling factor as either the slope between 2.H.2 and 1.A.2.e of all annual available values 1990-2021, where a positive ($r > 0$) and statistically significant ($p < 0.1$) relationship was calculated based on linear regression, or the median ratio across all years for a given country. A p-value threshold of 0.1 was chosen to retain as many country-specific sector linear relationships as possible, rather than relying on a single global relationship that could misrepresent individual countries' sectors. We then applied this ratio to the CEDS 1.A.2.e emissions value for each Annex I country to estimate direct emissions from food, beverage and tobacco manufacturing.

As this relationship does not hold for non-Annex I countries, we assumed negligible direct emissions from food, beverage, and tobacco production in non-Annex I countries. Methane (CH_4) and nitrous oxide (N_2O) direct emissions were assumed to be unknown, and filled using the default data fusion methodology (Moore et al. 2025).

The equation for estimating country-level food-beverage-tobacco CO_2 emissions was then defined as:

food-beverage-tobacco = food-and-beverage-direct +
CEDS 1A2e_Ind-Comb-Food-tobacco

where,

If non-Annex I countries:
food-and-beverage-direct = 0

Else:
food-and-beverage-direct = [[UNFCCC 2.H.2 / CEDS 1A2e_Ind-Comb-Food-tobacco]]
× CEDS 1A2e_Ind-Comb-Food-tobacco

Where, [[UNFCCC 2.H.2 / UNFCCC 1.A.2.e]] represents either the country-specific slope of the least squares line between the emissions from these two subsectors (where $r > 0$, $p < 0.1$), or the median ratio (else).

2.1.3.1.2 Glass

Glass manufacturing consists of both direct (2.A.3) and indirect (1.A.2.f) emissions. However, in CEDS, indirect emissions are aggregated together with indirect emissions from all non-metallic minerals (including cement, lime, and other carbonates). In order to disaggregate these indirect emissions, we estimated the contribution of glass combustion to CEDS 1.A.2.f by assuming that the ratio of direct to indirect emissions for each of these four mineral subsectors (i.e. glass, lime, cement, and other carbonates) were equal. With that assumption we calculated the relative contribution of glass direct emissions (2.A.3) to the sum of direct emissions from each individual subsector (i.e. 2.A.1 + 2.A.2 + 2.A.3 + 2.A.4), and multiplied that by the total indirect emissions (1.A.2.f). Therefore, the equation to estimate total glass manufacturing emissions is:

glass = EDGAR 2.A.3 Glass + glass-combustion

where,

glass-combustion = (CEDS 1A2f_Ind-Comb-Non-metalic-minerals) ×
EDGAR 2.A.3 Glass / (EDGAR 2.A.1 Cement + EDGAR 2.A.2 Lime +
EDGAR 2.A.3 Glass +
EDGAR 2.A.4 Other Process Uses of Carbonates)

2.1.3.1.3 Lime

Similarly to glass manufacturing, lime manufacturing consists of both direct and indirect emissions, the latter of which needs to also be disaggregated for CEDS data. Following the same formulation described above for glass manufacturing, the equation for calculating emissions from lime manufacturing is:

lime = EDGAR 2.A.2 Lime + lime-combustion

where,

lime-combustion = (CEDS 1A2f_Ind-Comb-Non-metalic-minerals) × EDGAR 2.A.2 Lime / (EDGAR 2.A.1 Cement + EDGAR 2.A.2 Lime + EDGAR 2.A.3 Glass + EDGAR 2.A.4 Other Process Uses of Carbonates)

2.3.1.4 Textiles, leather, and apparel

Here, CEDS textile and leather combustion-related emissions is set to "*textiles-leather-apparel*" which can contain, including but not limited to, linen, polyester, and silk.

textiles-leather-apparel = CEDS 1A2g_Ind-Comb-textile-leather

Note, at the country-level, this sector is filled using the "Implicit estimation" technique, but is included here, as its asset-level data are estimated using the "data-informed disaggregation" technique.

2.1.3.2 Asset-level data

Assets were obtained for the following sectors: *other-metals*, *other-chemicals*, *other-manufacturing*, *glass*, *lime*, *food-beverage-tobacco*, and *textiles-leather-apparel*. Emission quantities for each sector were obtained from their respective sources, where available. Due to a lack of production-level information, the metadata for *other-metals*, *other-chemicals*, *other-manufacturing* were limited to: capacity = activity = 1 facility. Therefore, emission factors describe the emissions of a given gas, per facility. Emissions and emissions factors for assets with no available data were imputed using the default metamodeling methods, described in Moore et al. (2024). For assets in the remaining four sectors, the following sections outline the Data-informed Emissions Disaggregation approach applied to obtain complete emissions values and associated metadata.

2.1.3.2.1 Asset Metadata Pre-processing

Asset-level annual data were often only available, if at all, for select years. Therefore, in order to achieve complete temporal coverage for 2015 - 2024 (2024 is the final year because it is the final year of data from all needed external inventories), annual values were backward and then forward filled. For instance, if information for a given asset was only known for 2020 - 2021, the 2020 value was backward filled for 2015 - 2019, and the 2021 value was used for years 2022 through the remainder of the timeseries.

2.1.3.1.2 Asset Emissions Factors

Country-specific CO_2 emissions factors for assets were calculated as the country-level emissions divided by the sum of country activity, by year. CO_2 emissions factors were then each divided by a correction factor, f (see 2.1.3.1.3), to adjust for discrepancies between country-level emissions and the sum of asset-level emissions, in the context of the number of inferred emitting sources. CH_4 and N_2O emissions factors were calculated after all asset-level emissions and activity were determined (see the following sections).

2.1.3.1.3 Asset Capacity and Activity

Below, assets used in each sector but without capacity and activity information were derived using approaches specific to each sector

Lime. Capacity and activity for lime production were handled separately and more traditionally than the other subsectors. The reason is twofold: first, because country-level production statistics (i.e. tonnes of lime produced per year) are available from the USGS for most countries where we were able to obtain asset-level information, and second because some asset-level production data were obtained. Capacity was defined as the total capacity of lime production (in tonnes) and the activity was defined as the total lime produced (in tonnes).

Where both country-level and asset-level production data (i.e. activity) were available for a given country, the sum of asset-level activity was subtracted from the country's total activity, and where the remainder was positive, it was disaggregated equally to the remaining assets. Where the remainder was negative, the sum of asset-level activity replaced the country total, and any remaining asset level activities were filled in using the default data fusion methodology where the country average was applied.

Asset-level capacities were estimated using the average capacity factor (i.e. capacity / activity) for assets in China where both capacity and activity were quantified.

Glass, food-beverage-tobacco, and textiles-leather-apparel. For these three subsectors, country-level economic data were used as a proxy for production, and defined the activity and capacity (in U.S. dollar or USD) at the asset level. Country-level output, in USD, and the number of establishments were obtained from UNIDO.

Specifically, for *food-beverage-tobacco* and *textiles-leather-apparel*, the number of establishments from UNIDO consisted mostly of non-emitting facilities in each industry (e.g. offices, etc.). Therefore, for each of these subsectors, the number of *emitting* establishments was calculated using the ratio of scraped assets deemed to be emitting to the total number of scraped assets, globally (e.g. considering only 'wet processing', 'dye/dyeing', 'fiber processing', 'tannery' as emitting facilities in *textiles-leather-apparel* to filter out offices/headquarters, for instance). For any country where the number of scraped assets was greater than the UNIDO-estimated number of emitting assets, the number of scraped assets replaced the country total. For *glass*, we assumed that, for any country for which we have obtained scraped assets, we have 100% coverage, so the number of establishments from UNIDO was ignored.

Because country-level output and number of establishments were not available for all years and countries, forward and backward filling was applied to fill time gaps in the data, and the median ratio of output to number of establishments were used to fill in information for missing countries.

For assets with known emissions (see 2.1.3.1.4), activity and capacity were derived as the emissions divided by the emissions factor multiplied by a correction factor, *f* (see below). For all other assets, asset-level capacity and activity, country-level activity was divided by the number of emitting assets to obtain a country-specific value for output-per-asset for each year. This value, multiplied by the correction factor, *f*, then defined the activity and capacity for each asset in that country.

Other. The capacity and activity for all remaining sectors were defined as '1 factory', due to 1) a lack of production data at the country-level, and/or 2) lack of specificity of the industry subsector to allow for more precise production estimates at either the country or asset level.

Correction factor, f. A correction factor, *f*, was needed to adjust for discrepancies between country-level emissions and the sum of asset-level emissions, in the context of the number of inferred emitting sources. Beginning with,

$$A_c = (\sum_{i}^{N'} a_i + \sum_{j}^{N''} \frac{e_j}{\epsilon})f$$

where, A_c is the country-level activity, N' is the number of assets with unknown emissions for that country, a_i is the asset-level activity for the *i*th asset with unknown emissions, N'' is the number of assets with known emissions for that country, e_j is the asset emissions for the *j*th asset with known emissions, ϵ is the country-level emissions factor before correction. It follows, then, that

$$f = \frac{1}{\frac{N'}{N} + \frac{\hat{E}}{E}}$$

where, $\hat{E}$ is the sum of asset-level emissions for assets with known emissions and N is the total number of assets (both with known and unknown emissions).

To maintain consistency across assets, the correction factor adjusts both the activity and emissions factor such that emissions are left unaltered. Specifically, activity was multiplied by *f*, while emissions factors were divided by *f*. In the case where N' was 0 (i.e. no assets with unknown emissions), *f*=1. In contrast, if $\hat{E}$ is equal to E (i.e. all country-level emissions are accounted for by assets with known emissions) but N' does not equal N (i.e. the data infer that there are more emitting assets beyond what are accounted for in this dataset), then the correction factor becomes nonzero, scaling down asset-level activity and scaling up emissions factors, thereby inferring missing emissions.

2.1.3.1.4 Asset Emissions

A subset of scraped assets included emissions estimates, which were backward and forward filled for time-series completeness. For each country, gas and year, the sum of scraped asset emissions replaced the country-level estimate where the sum of assets was greater. In order to assign emissions to the remaining assets, a country-level emissions factor was calculated as the country's total emissions divided by the country's total activity (i.e. output in USD for *food-beverage-tobacco*, *glass*, and *textiles-leather-apparel*, and production in tonnes for *lime*). This emission factor was then applied to the asset-level activity to estimate emissions.

Finally, where the sum of emissions from scraped assets was greater than the estimated country total emissions for a given sector and gas, remaining assets with no emissions were left as NULL, to be filled in using the default data fusion methodology (see Moore et al. 2025) wherein the country average emissions were used to infer unknown values. Subsequently, the sum of asset emissions replaced the existing country total (Figure 1).

2.3.1.5 Asset Confidences

Confidences were assigned on a 5-point scale ('very low' to 'very high'). Where data was obtained directly from scraped databases for a given asset, gas, and year, a confidence value of 'medium' was assigned. Where values were forward or backward filled in time for a given asset and gas, a confidence of 'low' was assigned. For all other imputed or otherwise estimated values, as described above, a confidence of 'very low' was assigned.

2.3.1.6 Asset Uncertainties

Uncertainties were filled using the default data fusion methodology (see Moore et al. 2025).

2.2 Implicit Estimation of Other Subsectors

For sectors where there was incomplete or no asset level data, the implicit estimation approach was used, which employed GHG inventories, projected emissions data to fill in missing years in GHG inventories, and developed sector specific equations to output implicit estimation for the sectoral "other" emissions. Sectors estimated using this method, are directly equal to their source dataset.

2.2.1 Datasets employed

Climate TRACE GHG emissions inventory data (Climate TRACE 2025; https://climatetrace.org/): Climate TRACE is a global coalition of organizations with each organization focusing on measuring CO_2, N_2O, and CH_4 emissions from particular economic or land cover sectors.

Temporal coverage: Climate TRACE country-level data is provided for 2015-2024 with 2025 emissions either partially or fully projected, depending on temporal coverage for individual sectors. The data are typically released with a 3-4 month latency. For example, data released in November are generally provided through June of the same year, with the remaining months projected.

Sectoral coverage: Climate TRACE sectors using techniques 1, 2, 3 and 4 total 81% of global emissions. Emissions that are not currently estimated using techniques 1 to 4 were measured using the implicit estimation method. By employing all techniques described here, Climate TRACE country-level inventory accounts for 100% of known anthropogenic greenhouse gasses based on IPCC and UNFCCC reporting.

Geographic coverage: Emissions estimates for Climate TRACE measured sectors are available for every country in the world. Comprehensive data are not available in some disputed territories due to lack of data availability.

Food and Agriculture Organization of the United Nations (FAOSTAT) is a specialized agency of the United Nations that focuses on agriculture and food security. FAO is also tasked with collecting food, agriculture and land use, land-use change and forestry (LULUCF) data from countries around the world regarding their agricultural and forestry activities and emissions.

Temporal coverage: FAOSTAT data is available from 1990 - 2022 at the time of data was accessed (August 13, 2025). Data is released on a two year delay. For example, 2019 data was released in 2021.

Sectoral granularity and coverage: FAOSTAT data is available only for agriculture and LULUCF sectors.

Geographic coverage: FAOSTAT data is global and covers 233 countries and territories (FAOSTAT, 2024).

The Emissions Database for Global Atmospheric Research (EDGAR) is an independent database of anthropogenic GHG emissions, providing both national totals and gridmaps. Though the gridmaps are highly granular, we only used the national totals for the purposes of this exercise.

Temporal coverage: EDGAR data is available for the years 1970-2023 (EDGAR v8.0). The complete data is published on an irregular lag. For example, 2018 data was published in May of 2021 and data for 2019, 2020 and 2021 was published in September of 2022. However, EDGAR released data for 2022 in October 2023 and Climate TRACE was able to use these updated values for implicit estimation. EDGAR's 2023 release did not include fluorinated gases broken down by gas. In order to be able to estimate CO_2 equivalent 20- and 100-year global warming potentials (CO_2e 20yr and 100yr GWP), Climate TRACE needed the individual greenhouse gas numbers. For this reason, Climate TRACE utilized EDGAR's previous release (EDGAR v7.0) which provides individual GHGs and forward filled 2021 data to 2024 for fluorinated gases to generate CO_2e 20yr and 100yr GWPs that include all GHGs .

Sectoral granularity: EDGAR data covers all IPCC emissions except for LULUCF. However, the sectors are not as granular as the most granular IPCC categories. For example, EDGAR reports emissions for 1.B.1 Solid Fuels but does not break it down into 1.B.1.a Coal Mining, 1.B.1.b Solid Fuel Transformation, 1.B.1.c Other.

Geographic coverage: EDGAR data is globally comprehensive.

The Community Emissions Data System (CEDS) developed by the Pacific Northwest National Laboratory is an annually updated emissions dataset that estimates anthropogenic emissions for all major emission species (GHGs and non-GHG), providing both country-level and gridded emissions data.

Temporal coverage: CEDS data is available for the years 1750-2023 (v_2025_03_18).

Sectoral granularity: CEDS data covers all IPCC emissions except for LULUCF and biomass burning.

Geographic coverage: CEDS data is globally comprehensive.

2.2.2 Methods

2.2.2.1. Projection approach

Not all GHG inventories have the most recent emissions estimates. EDGAR v8.0 currently provides data up to 2023, and FAOSTAT published data up to 2022. In order to utilize the FAOSTAT data for implicit estimation, the data was forward filled up to the final Climate TRACE release month . This method uses the last available estimate as the future projected values. This approach was adopted to ensure all GHG inventories described in section 2.1 match temporally.

2.2.2.1 Implicit Estimation approach - equations

An immediate practical challenge in implicit estimation is that different global emissions inventories do not use one consistent standardized hierarchy of definitions for emitting sectors and subsectors. Thus, Climate TRACE's first step was to define a crosswalk of all emitting subsectors from all inventories it could find, to enable comparison between Climate TRACE sector lead results and those of existing publicly available global emissions inventories. This crosswalk can be found in Table S1 in the Supplementary section.

With the knowledge of what is covered by Climate TRACE vs. EDGAR and FAOSTAT, we were able to write equations to describe the emissions that are not currently estimated using techniques 1, 2, or 3.

Example 1: Other Solid Fuels

Emissions from 'other solid fuels' are not currently measured at the asset level by Climate TRACE. WattTime and Global Energy Monitor are measuring coal mine activities' emissions and TransitionZero is measuring only CO_2 emissions from steel manufacturing, but neither of these models include emissions from solid fuel transformation and abandoned coal mines. Within the IPCC framework, coal mining is a subset of 1.B.1 Solid Fuels. EDGAR reports data for 1.B.1 Solid Fuels but does not report at the more granular levels such as 1.B.1.a Coal Mining and Handling. Figures 2 and 3 show the WattTime/Global Energy Monitor and EDGAR coverage, respectively for this sector.

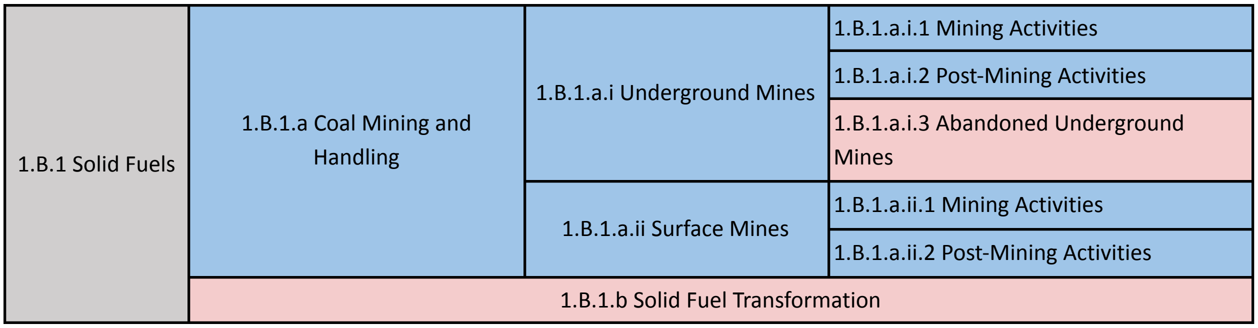

Figure 2 WattTime/Global Energy Monitor 1.B.1 Solid Fuels and subsectors coverage. Fully covered (in blue), not covered (in red), and partially covered (in gray).

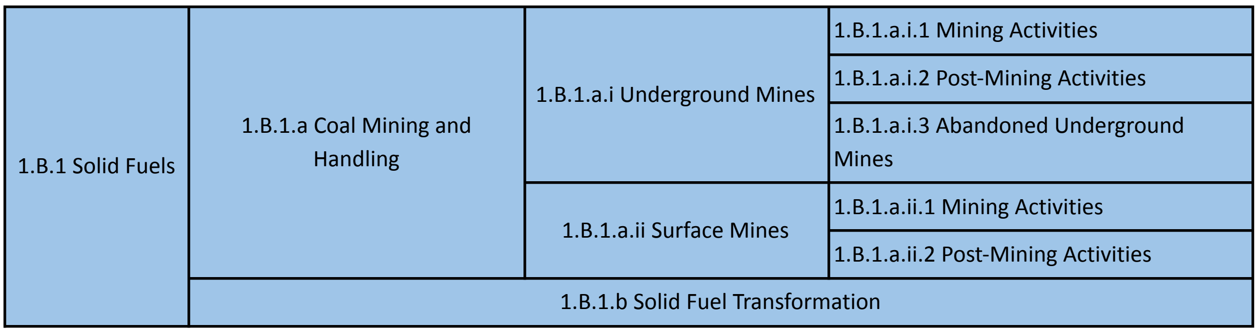

Figure 3 EDGAR 1.B.1 Solid Fuels and subsector coverage. Full covered (in blue), not covered (in red), and partially covered (gray).

Because EDGAR covers all of 1.B.1, subtracting WattTime/Global Energy Monitor's coal mining values from EDGAR results in an estimate for 1.B.1.b Solid Fuel Transformation.

Eq. Climate TRACE Solid Fuel Transformations = EDGAR 1.B.1 Solid Fuels - WattTime/Global Energy Monitor Coal Mining

The approaches highlighted in the examples were repeated for different sectors to estimate remaining emissions. All implicit estimation equations can be found in Table S2 in the Supplementary section.

Example 2: Other agricultural soil emissions

Agricultural soils include N_2O and other emissions from soils due to agricultural practices. While Climate TRACE estimates emissions from some agricultural sectors, like the application of synthetic fertilizers, other emissions from soils were estimated by using FAOSTAT and EDGAR data which reports emissions by subsector and were added together into a single subsector:

Other-agricultural-soil-emissions = FAOSTAT Manure left on Pasture-non cattle +
FAOSTAT Drained organic soils +
EDGAR 3.C.2 Liming +
EDGAR 3.C.3 Urea application

Example 3: Other Manufacturing
Compared to the v3.0.0 Climate TRACE release in 2023, the Other Manufacturing sector in v5.0.0 contains fewer subsectors, as they were further granularized either through technique 4 or through the introduction of the CEDS inventory (see Section 3.1 below and Table S2). Additionally, the remainder of the combustion (i.e. indirect) emissions from non-metallic minerals (1.A.2.f) described in Sections 2.1.3.1.2 and 2.1.3.1.3 must be accounted for here. This was done using the same formulation above and is denoted in the following equations as '*misc-combustion*'. Therefore, the equation for estimating the remaining, or 'other', manufacturing emissions is:

other-manufacturing = EDGAR 2.D non-energy products +
(EDGAR 2.A.X Other minerals - CEDS 2.A.3 Glass) +
CEDS 1A2g_Ind-Comb-Construction +
CEDS 1A2g_Ind-Comb-transpequip +
CEDS 1A2g_Ind-Comb-machinery +
CEDS 1A2g_Ind-Comb-other + misc-combustion

where,

misc-combustion = (CEDS 1A2f_Ind-Comb-Non-metalic-minerals) ×
EDGAR 2.A.4 Other Process Uses of Carbonates /
(EDGAR 2.A.1 Cement + EDGAR 2.A.2 Lime +
EDGAR 2.A.3 Glass +
EDGAR 2.A.4 Other Process Uses of Carbonates)

The Other Manufacturing sector derived here contains the following subsectors: combustion related to construction, transportation equipment, machinery, non-metallic mineral production (excluding glass, lime, and cement), as well as all other combustion (1.A.2.g), and non-energy products (2.D).

3. Results
The results below highlight the disaggregation and implicit estimation approaches outlined above. Unless otherwise noted, all CO_2 equivalent (CO_2e) estimates are in the 100 year timescale (AR6 global warming potentials).

3.1 Data-informed Emissions Disaggregation

Table 1 summarizes the total global GHG emissions from the disaggregated manufacturing sectors, which were all previously (v3.0.0) combined into the *other-manufacturing* sector. Overall, more than 50% of emissions, or roughly 2 billion tonnes CO_2e in 2024, previously categorized as *other-manufacturing* were disaggregated into these subsectors in Climate TRACE v5.0.0. Furthermore, we achieved asset-level coverage greater than 50% in four of the nine highlighted subsectors, with as much as 82% coverage for *lime* (Table 2).

Finally, the top five highest emitting countries in each sector are presented in Table 3. In every sector other than *other-metals* either China or the USA is the highest emitter, and in five of the nine sectors, these two countries hold the top two spots. In fact, there are only two sectors where either China or the USA falls outside the top five emitting countries (textiles-leather-apparel, USA; glass, China). The remaining high-emitting spots are largely sector-dependent, with Indonesia, for instance landing in the top-five for *other-metals* sectors, and *glass* being largely dominated by European countries, following the USA.

Table 1. Global totals of CO_2e emissions across the nine manufacturing subsectors, including the percent contribution of each subsector to the total global for all.

Sector	**2024 Emissions [Mt CO_2e]**	**% contribution**
food-beverage-tobacco	276	7.2
glass	42	1.1
lime	542	14.0
other-chemicals	799	20.7
other-manufacturing	1915	49.6
other-metals	186	4.8
other-mining-quarrying	33	0.9
textiles-leather-apparel	52	1.3
wood-and-wood-products	15	0.4
Total	3,904	100

Table 2. Asset-level coverage of 2024 GHG emissions per sector.

Sector	2024 asset-level emissions [Mt CO_2e]	% sectoral coverage
food-beverage-tobacco	157	57
glass	34	81
lime	446	82
other-chemicals	89	11
other-manufacturing	17	1
other-metals	38	20
textiles-leather-apparel	38	74

Table 3. Highest five GHG-emitting countries for each manufacturing subsector in 2024.

Country	*2024 Emissions [Mt CO_2e]*	*Country*	*2024 Emissions [Mt CO_2e]*
other-mining-quarrying		**other-chemicals**	
China	15.9	China	175.6
USA	3.4	USA	171.3
South Africa	2.6	Russia	45.7
Jamaica	1.1	Japan	43.0
Morocco	0.9	Iran	36.1
other-metals		**wood-and-wood-products**	
Indonesia	51.3	USA	4.9
Russia	48.9	China	2.3
USA	20.1	Canada	1.8
South Africa	11.0	Russia	1.4
China	9.8	Germany	0.5
food-beverage-tobacco		**textiles-leather-apparel**	
USA	87.2	China	18.9
China	50.6	India	4.5

Country	2024 Emissions [Mt CO_2e]
France	10.3
Germany	9.3
Spain	8.1
lime	
China	384.5
USA	37.1
India	17.9
Russia	14.1
Brazil	9.3

Country	2024 Emissions [Mt CO_2e]
Turkey	4.3
Argentina	2.6
Vietnam	2.1
glass	
USA	8.3
Great Britain	4.2
Germany	3.4
France	3.4
Russia	3.2

Country	2024 Emissions [Mt CO_2e]
other-manufacturing	
China	632.1
India	186.7
USA	129.2
Iran	114.7
Saudi Arabia	106.1

3.2 Implicit Estimation of All Other Subsectors

The goal of the implicit estimation technique is to complement Climate TRACE's estimates using techniques 1, 2, 3 and 4 with existing estimates. This serves two purposes:

1) Ensure Climate TRACE's end product is globally and sectorally comprehensive for ease of use.
2) Make Climate TRACE and other datasets interoperable enough that they can be compared statistically.

Figure 4 shows EDGAR and Climate TRACE global totals for 2015-2023. Climate TRACE totals are split into implicitly estimated and measured totals. It should be noted that the Climate TRACE's global estimates are between 8.4 and 9.1 Gigatonnes higher than EDGAR's for all years. This is due primarily to RMI's oil and gas estimates which indicate vast undercounting of methane in current oil and gas estimates. Table 4 provides the EDGAR and Climate TRACE emission differences.

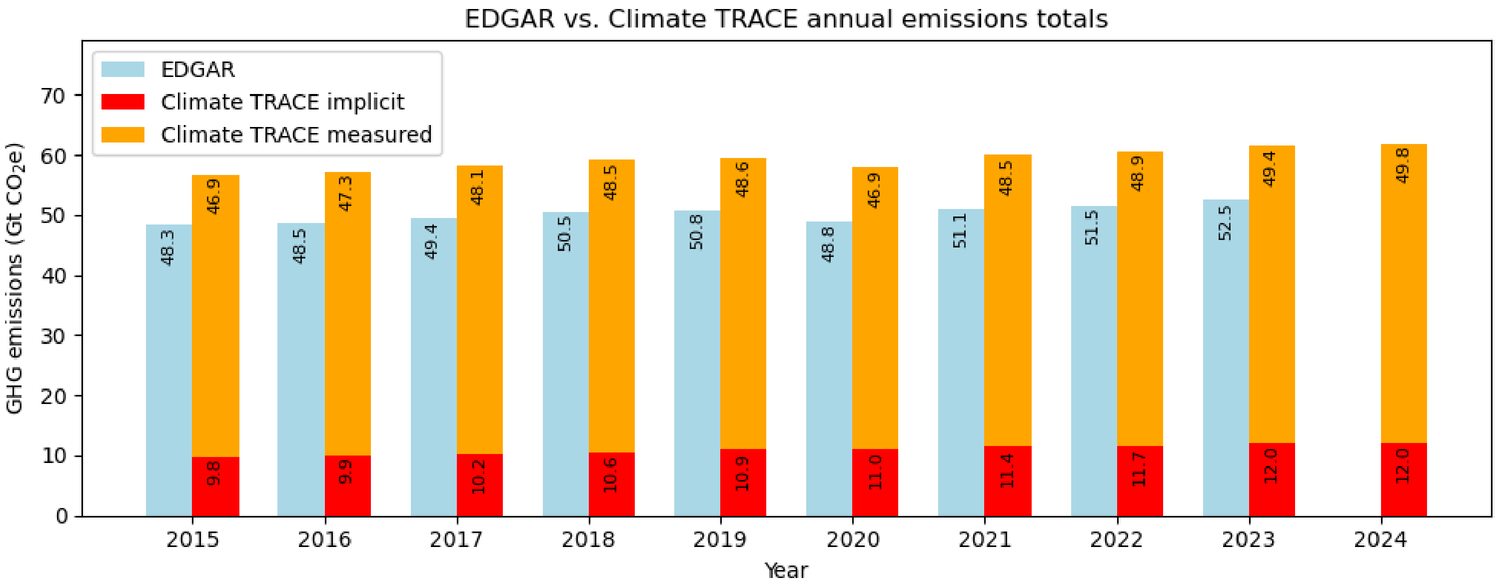

Figure 4 EDGAR global totals compared to Climate TRACE global totals for years 2015 to 2023. Climate TRACE totals are split into implicitly estimated and all other categories. Blue bars = EDGAR Totals, Red bars = Climate TRACE implicit estimation estimates, and Orange bars = Climate TRACE measured.

Table 4 Climate TRACE global totals versus EDGAR global totals, and the difference between the two by year. Emissions provided in Gigatonnes (GT).

Year	Global Climate TRACE emissions (GT CO_2e)	EDGAR CO_2e Emissions (GT)	Difference (GT CO_2e)
2015	56.7	48.3	8.4
2016	57.3	48.5	8.8
2017	58.3	49.4	8.9
2018	59.1	50.5	8.6
2019	59.5	50.8	8.7
2020	57.9	48.8	9.1
2021	59.9	51.1	8.8
2022	60.6	51.5	9.1
2023	61.5	52.5	9.0
2024	61.8	N/A	N/A

Figure 5 shows EDGAR totals compared to Climate TRACE totals for the top 10 highest emitting countries for 2023. China is the highest emitter, ~17.5 Gigatonnes, which is ~2.5 times more emissions than the USA (Table 5). Generally, Climate TRACE total estimates (measured and implicit estimate) result in higher emissions relative to EDGAR emissions.

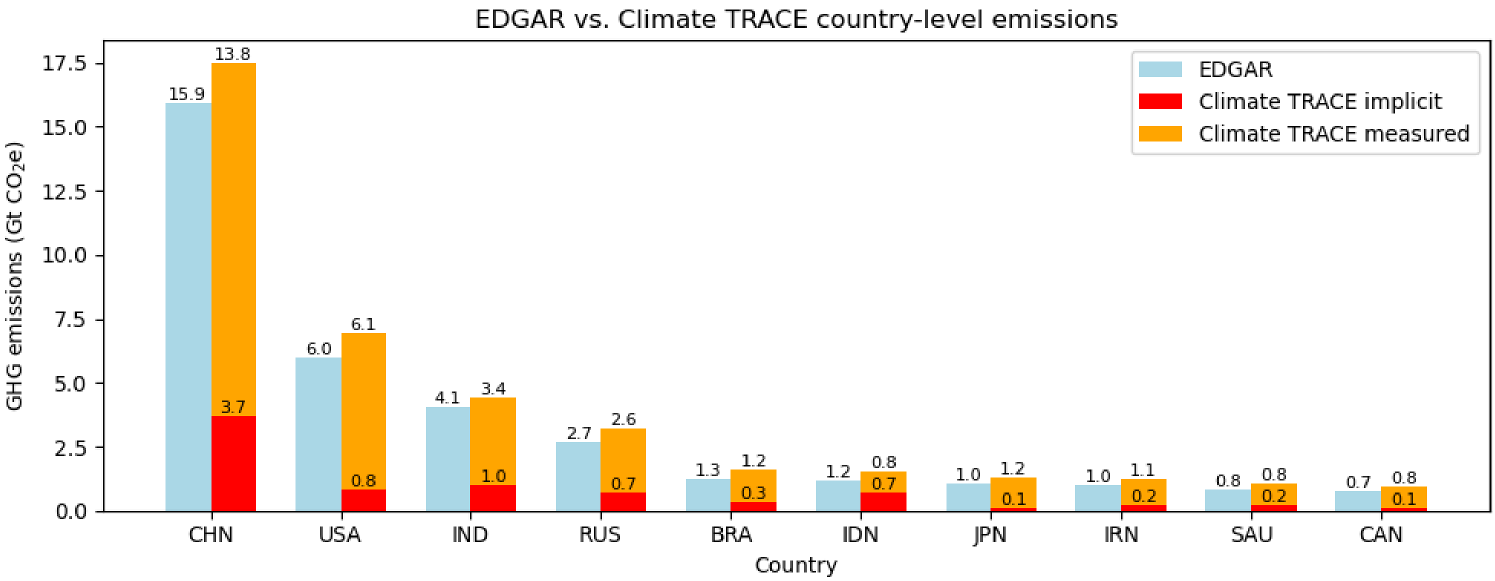

Figure 5 EDGAR totals compared to Climate TRACE totals for the top 10 highest emitting countries for 2023. Blue bars = EDGAR Totals, Red bars = Climate TRACE implicit, and Orange bars = Climate TRACE measured.

Table 5 EDGAR totals compared to Climate TRACE totals for the top 10 most emitting countries in 2023. Emissions provided in Gigatonnes (GT).

Country	EDGAR Total (GT CO_2e)	Climate TRACE Total (GT CO_2e)	Climate TRACE estimated using techniques 1, 2,3 or 4 (GT CO_2e)	Climate TRACE implicitly estimated (GT CO_2e)
CHN	15.92	17.49	13.76	3.73
USA	5.95	6.93	6.12	0.81
IND	4.07	4.40	3.42	0.98
RUS	2.66	3.25	2.56	0.69
BRA	1.27	1.60	1.25	0.35
IDN	1.17	1.53	0.81	0.72
JPN	1.04	1.30	1.19	0.11
IRN	0.99	1.27	1.07	0.20
SAU	0.81	1.03	0.82	0.21
CAN	0.74	0.94	0.82	0.12

3.2.1 Verifying results

We went through several systematic audits of the results to ensure that the implicit estimation equations were properly applied using all available relevant data. For instance, due to differences in how inventories specify country names, we ensured that standardized International Organization for Standardization (ISO3) codes were used to match up data points for each implicit calculation.

Results were not reported in cases where inventories define the actual emitting country differently. For example, EDGAR reported data for Serbia and Montenegro as one country. Climate TRACE and FAOSTAT report them separately since they have become separate legal entities since 2006. Therefore, results relying on EDGAR data for such countries were excluded from reported results. Similarly, results for some sectors are not included for countries in the Climate TRACE dataset where EDGAR and/or FAOSTAT do not provide emissions estimates.

3.2.2 Negative results from the implicit estimation approach

In some cases, implicit estimation equations resulted in negative emissions estimates. We identified two main reasons for this:

1. There is a large disparity between emissions estimates from different inventories for the relevant sectors.
2. Data from relevant sectors are missing from one of the inventories.

Examining the causes of negative results can identify discrepancies that are relevant to comparing estimates between inventories. Overall, 6.6% of implicit estimation results were negative in the dataset. However, they were distributed across just 7 out of the 19 sectors in the analysis. These results are highlighted in Tables 6 and 7. Climate TRACE replaces the negative numbers with 0 in the final inventory.

Table 6 Sum of negative implicit estimate results by sector (tonnes CO_2e) in v5.0.0 release.

Year	*Other Chemicals*	Other Energy Use	Other Fossil Fuel Operations	Other Manufacturing	*Other Metals*	*Other Mining Quarrying*	Other Solid Fuels
2015	-3,324,727	-396,369,431	-3,315,534,134	-477	-1,483,363,150	-97,183,806	-619,250,609
2016	-3,172,359	-344,563,436	-3,325,478,303	-475	-1,509,476,603	-101,541,803	-698,396,463
2017	-3,421,487	-327,997,587	-3,429,501,608	-474	-1,654,072,552	-92,518,674	-656,212,772
2018	-2,854,537	-367,934,569	-3,496,853,948	-472	-1,426,726,849	-97,442,368	-562,139,461
2019	-3,665,806	-377,433,498	-3,419,810,325	-470	-1,515,414,125	-103,094,097	-507,660,195
2020	-2,070,680	-421,843,155	-3,176,126,127	-517	-1,941,461,611	-116,072,517	-507,042,927
2021	-4,728,700	-408,775,333	-3,240,865,976	-579	-1,604,261,313	-133,544,358	-567,992,529
2022	-4,685,853	-533,594,108	-3,222,397,469	-579	-1,557,450,884	-148,787,461	-574,330,765
2023	-4,549,027	-571,331,771	-3,137,787,948	-579	-1,496,877,992	-151,495,510	-538,614,225

Table 7 Number of countries with negative implicit estimate results by sector in v5.0.0 release

Year	Other Chemicals	Other Energy Use	Other Fossil Fuel Operations	Other Manufacturing	Other Metals	Other Mining Quarrying	Solid Fuel Transformation
2015	14	131	81	3	74	86	30
2016	14	134	83	3	76	87	32
2017	15	124	83	3	77	90	31
2018	14	128	83	3	77	83	28
2019	14	126	84	3	75	83	27
2020	11	136	83	3	75	91	27
2021	12	126	84	3	79	89	29
2022	13	134	84	3	76	88	29
2023	15	137	89	3	77	90	29

4. Implications and future work

The two methods outlined here have many strengths, namely:

1. **Inventory completeness**: Although Climate TRACE's long-term goal is to estimate all emissions down to the source/asset, these approaches ensure that no emissions are being excluded from country/ sector totals;
2. **Estimates for low-information facilities**: Many manufacturing sector facilities– particularly those in countries without extensive publicly available databases– have little to no emissions data available at the facility level. The data informed disaggregation approach utilizes available information to create a first-order emissions estimate. As more

data are gathered – such as more granular economic data or additional information about the facilities, these estimates can be iteratively improved.

3. **Novel inventory crosswalk**. By defining all third party GHG inventory sectors by their IPCC reporting categories, Climate TRACE was able to make comparisons that would have otherwise been difficult. These comparisons also identify countries/ sectors where there are the largest discrepancies among all the inventories;
4. **Combining multiple estimates increases trust**. Every technique for estimating GHGs, especially at a global level has pros and cons. Some are highly granular and accurate but can be expensive (such as ground-level monitoring from CEMS units) and not comprehensive. This implicit estimation approach created by Climate TRACE for the 2023 launch lays the groundwork for more extensive Bayesian metamodeling that combines many sources of information to improve emissions estimates.

4.1 Limitations of Data-informed Emissions Disaggregation

The purpose of this work was to disaggregate, at multiple levels, existing emissions inventories. The first level of disaggregation, presented formally in Section 2.3.1, served to granularize emissions from existing inventories (e.g. EDGAR and CEDS), where multiple subsectors are combined. While this is sufficient from a broad perspective, one major goal of Climate TRACE is to continue building the largest and most comprehensive database of asset-level emissions, including associated metadata. Thus, the second level of disaggregation, outlined in section 2.3.2, relates to the attribution of emissions and production to the individual asset level.

There are limitations to the framework presented:

1. There is a lack of sector-specific production data that makes even country-level estimation challenging. Therefore, a future goal of this work is to obtain more accurate and granular information of industry production at the country-level, which will be used to inform more accurate estimates of asset-level activity, and therefore emissions.
2. Although this dataset contains the greatest number of emitting assets for the subsectors presented here, asset-level information in most countries is still lacking. Therefore, future work will strive to achieve 100% coverage of each of these sectors.
3. Throughout the methodology, there are instances where statistics are used to inform estimates for countries where little to no information is known. Although this constitutes a minority of emissions, such imputations may lead to inaccuracies in some countries, both at the country and asset levels.

Addressing each of these limitations in future iterations of this dataset will be of primary interest to increasing its completeness and improving its accuracy.

4.2 Limitations of the implicit estimation approach

1. **Low confidence estimates.** This method makes use of estimates that are not based on direct observations. Climate TRACE's roadmap will be to downweigh such estimates in future metamodeling and upweight estimates based on direct observations.
2. **Novel estimates.** In sectors containing one or more implicitly estimated subsectors, any potential errors in the source data potentially affects the sector total, not just the implicitly estimated subsector total. As long as the sum of subsectors measured using techniques 1, 2, and 3 (from the introduction) are less than the sum of the implicitly measured subsectors, then the sector total will match exactly the source data used to implicitly estimate the remaining sectoral "other" emissions (Figure 6). For example, the sum of Climate TRACE's mining and manufacturing sector estimates is almost always lower than the sum of the corresponding EDGAR subsectors. The implicitly estimated sector, Other Manufacturing, will always cause the sum of all Climate TRACE manufacturing sectors to equal the sum of EDGAR's manufacturing sectors. Therefore, this method is useful for detecting underestimates in the original source data. However, if the estimated total is an overestimate, it may not correctly detect it.
3. **Lack of specificity in implicitly estimated sectors.** This method does not reveal emitting source level results or identify the exact cause of emissions in implicitly estimated sectors.
4. **Reliability of source datasets.** EDGAR generally publishes estimates on a lag of 1 year. EDGAR has been annually publishing updates in the fall of every year since. However, the EDGAR release schedule is not published to the public. In the absence of up-to-date datasets for implicit estimation, Climate TRACE will need to create projections to fill in missing years using the most recently available data.
   Likewise, the most recent published data from FAOSTAT is currently 2022 at the time of this work. Climate TRACE forward fills this data for the 2023 to 2025 estimates.
   Thus, Climate TRACE's priorities for future implicit estimation are to incorporate as many emissions inventories as possible, produce similar systems of equations to make them interoperable as possible, and produce parsimonious consensus results based on large numbers of independent cross-validations.

5. Emission Reduction Solutions

Identifying ways to reduce emissions is a key goal for Climate TRACE. Here potential emission reduction solutions (ERSs) are provided for each sector estimated in this methodology to understand how mitigation strategies can reduce emissions. *Note: Only rank 1 strategies are provided for assets on the Climate TRACE website and additional strategies will be made available in future releases.*

5.1 biological-treatment-of-solid-waste-and-biogenic - CH_4 Flaring

The proposed ERS involves collecting methane produced through anaerobic digestion and flaring it, thereby converting CH_4 into CO_2. Because methane has a higher global warming potential than CO_2, flaring reduces the overall climate impact of waste management. Of the waste diverted for biological treatment, around 40% could be anaerobically digested and captured for flaring. Flaring systems operate at approximately 90% efficiency, which translates to a potential total emissions reduction of roughly 36% from the treated waste stream. This methodology accounts for both the methane emissions reduction and the associated mitigation of greenhouse gas warming potential.

Many countries and landfills already employ methane flaring to limit the warming impact of organic waste decomposition. While the approach is effective, technological and financial constraints may hinder global adoption, particularly in regions lacking infrastructure or funding for anaerobic digestion and flaring systems.

5.2 food-beverage-tobacco - Thermal management and waste heat recovery

Thermal management and waste heat recovery in the food, beverage, and tobacco production sectors target emissions associated with process heat, which constitutes 60–70% of energy-related emissions in many facilities. These emissions arise from heat used in processing food materials, waste treatment, and fermentation, with the most energy-intensive processes including animal slaughter, grain milling, dairy production, fruit and vegetable preservation, and baked goods preparation. The strategy focuses on improving thermal efficiency through better insulation, enhanced waste heat recovery, and the application of pinch technology, which optimizes energy transfer where hot and cold utilities are closely matched.

The mechanism of this approach reduces energy consumption and associated emissions, with potential reductions ranging from 5% to 95% depending on the process, and an average reduction of 30% was assumed for modeling purposes. Adoption is already occurring widely, driven primarily by the incentive to reduce energy costs. Industries that implement these measures benefit both economically and environmentally, as energy savings translate directly into lower greenhouse gas emissions.

5.3 glass - Convert production configuration

In glass manufacturing, the majority of greenhouse gas and gaseous emissions result from melting raw materials in high-temperature furnaces, where fossil fuel combustion and the decomposition of carbonates release CO_2 and other pollutants. These emissions are generated directly within the glass furnace during the fusion of silica, soda ash, and other inputs into molten glass, contributing roughly 0.1% of global CO_2-equivalent emissions. The strategy of converting production configuration focuses on adopting oxyfiring with natural gas boilers and recovering waste heat to improve efficiency and reduce emissions from the manufacturing process.

This ERS strategy achieves approximately an 11.5% emissions reduction compared to processes that rely solely on fossil fuel combustion. The increased efficiency also leads to co-benefits, including reductions in other pollutants such as NOx and SOx. The method has been widely tested and demonstrated with a technology readiness level of 8–9, indicating high maturity and readiness for industrial deployment.

5.4 incineration-and-open-burning-of-waste

The incineration-and-open-burning-of-waste produces GHGs and non-GHGs, contributing to global emissions and impacting local health. Here, two ERS strategies are proposed for this sector.

5.4.1 Divert organic waste from landfills and compost/capture

Open burning of waste is common in regions with limited waste management infrastructure, and waste incineration is both inefficient and a source of pollutants harmful to human health. A solution to reduce these emissions is to sort waste, diverting organic materials to composting or capturing methane, and separating recyclables from landfill streams. By diverting organic waste to composting, waste incineration emissions can be reduced by approximately 85%. Many communities have already implemented composting programs and methane capture initiatives, demonstrating the feasibility of this approach. However, technological and financial constraints may limit global adoption, particularly in regions lacking the necessary infrastructure or resources (Environment America, 2025).

5.4.2 Domestic waste management infrastructure

Open burning of waste is prevalent in regions with inadequate waste management infrastructure, and waste incineration is inefficient while releasing pollutants that harm human health. A practical solution is the adoption of decentralized domestic waste management practices, including neighborhood-level composting and recycling projects, which can significantly reduce emissions from open burning. By implementing collection and processing programs for recycling and composting, waste incineration activity can be effectively eliminated. Many communities already operate such programs, demonstrating feasibility, but financial constraints may limit global adoption (Environment America, 2025).

5.5 lime - Energy from biomass

Lime production generates greenhouse gas and other gaseous emissions primarily during the calcination of limestone, where heating in kilns releases CO2 both from fuel combustion and the chemical decomposition of calcium carbonate, contributing roughly 0.9% of global CO2-equivalent emissions. One effective strategy to reduce these emissions is the use of biomass for energy needs during production, replacing fossil fuel combustion, which is generally more emissions-intensive. By substituting fossil fuels with biomass, overall emissions from lime production can be reduced by approximately 30%. This approach has a high technology readiness level (TRL 8), indicating that fuel conversion to biomass is a mature and implementable method within the industry (Shen et al., 2024).

5.6 manure-management-other - Slurry removal system

Methane and nitrous oxide emissions from manure management practices not included in other sub-sectors account for nearly 0.4% of global CO_2-equivalent emissions. A strategy to reduce these emissions is the implementation of improved slurry removal systems, where slurry is removed from animal housing more frequently. By employing this strategy, methane emissions can decrease by 65–80% and nitrous oxide emissions by 12–30%, with calculations for this methodology assuming reductions at the lower end of these ranges. Technologically, this approach is feasible as it does not require complex new systems, though adoption has so far been tested only in limited settings. The strategy can be integrated into existing manure management operations to reduce greenhouse gas emissions without significant infrastructural changes (Aneja et al., 2023; von Keyserlingk et al., 2023).

5.7 other-agricultural-soil-emissions - Enhanced rock weathering (ERW)

Agricultural soils, excluding fertilization and manure application, release CO_2, CH_4, and N_2O through microbial processes including the decomposition of organic matter and wetting-drying cycles. These emissions contribute approximately 2.2% of global CO_2-equivalent emissions. Enhanced rock weathering (ERW) is a strategy that applies finely ground silicate minerals to soils, where they react with CO_2 in the soil and atmosphere to form stable carbonates. This process lowers soil CO_2 levels and can indirectly improve soil pH and nutrient balance, potentially mitigating conditions favorable to greenhouse gas emissions, though reductions in N_2O are not considered here. Using the emission source curve provided in the literature, ERW is estimated to reduce annual emissions by roughly 35%; when accounting for emissions related to electricity used to produce the minerals, the net reduction is approximately 20% relative to the baseline. While ERW shows potential for substantial impact, it remains a promising but underexplored approach (Beerling et al., 2024).

5.8 other-chemicals - Alternative fuel use and cleaner production

Chemical production of hydrogen, nitric acid, titanium oxide, and other minor chemicals generates greenhouse gas emissions and other pollutants primarily through fuel combustion and process reactions involving oxidation or reforming steps. These processes release CO_2, N_2O, and small amounts of other pollutants directly from reactors, reformers, or kilns used in chemical conversion and purification. Emissions can be mitigated through the use of alternative energy sources such as waste heat recovery and renewable energy, alongside efficiency improvements, as well as cleaner production processes including methane leak reduction and carbon capture. Implementation of alternative energy sources reduces emissions by approximately 15%, while cleaner production processes further reduce emissions by over 15%, resulting in an overall estimated reduction of around 30%. These practices have been widely adopted and have demonstrated improvements in operational efficiency and emissions reductions (RMI, 2025).

5.9 railways - Electrification of railways

Railways are a source of GHG emissions through fossil-fuel usage, accounting for approximately 0.2% of global CO_2-equivalent emissions. Emissions can be reduced by increasing railway electrification, leveraging historical trends of electrification and greater usage of electrified railways for freight. Implementing this strategy could decrease greenhouse gas emissions by roughly 40%, including the emissions associated with electricity generation. Electrification of railways has been widely adopted, particularly for passenger transport, and many countries plan to expand the use of electrified rail for freight as well (Drawdown, 2025).

5.10 fluorinated-gases - Replace HFCs and HCFCs with low GWP alternatives

Replacing hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) with low-global warming potential (GWP) alternatives targets fluorinated gases, which, although present in relatively small atmospheric concentrations, have extremely high GWPs and long atmospheric lifetimes, making them some of the most potent anthropogenic greenhouse gases. HFCs are predominantly used as refrigerants in residential, commercial, and industrial air conditioning and refrigeration systems, and are also found in foam production, aerosol sprays, fire suppression systems, and as solvents. The proposed solution involves substituting these high-GWP compounds with natural refrigerants or low-GWP synthetic alternatives, which significantly lowers emissions from these systems.

This strategy addresses approximately 90% of HFC usage in residential, commercial, and industrial applications, focusing particularly on the 86% derived from refrigeration, air conditioning, and heat pump systems. Adoption of low-GWP alternatives, such as hydrocarbons, carbon dioxide, hydrofluoroolefins (HFOs), or blended refrigerants like R32 and R454B, can reduce GWP-weighted emissions by 50–90%, with a conservative average reduction of 70% assumed for this analysis. The mechanism relies on either retrofitting existing equipment or replacing systems at the end of their operational life, ensuring that emissions from these high-impact sources are minimized.

Adoption of low-GWP refrigerants is expanding globally, driven by regulations such as the Kigali Amendment and sector-specific emissions reduction targets. Implementation has been effective in commercial and industrial refrigeration, with innovations in recent years accelerating the deployment of these alternatives. Nonetheless, practical adoption requires careful assessment for each application due to variations in thermodynamic and safety properties. Local climate, regional conditions, and system-specific constraints can influence the choice of refrigerant, meaning there is no universal solution applicable to all contexts (European Commission, 2025; UNEP, 2015; EPA, 2025).

5.11 other-mining-quarrying - Electrification of mine equipment

Greenhouse gas emissions from the mineral extraction sector are primarily generated by the combustion of fuels from mobile sources, such as vehicles and machinery, and fixed sources like generators, particularly at sites without access to electricity grids. Emissions can be significantly reduced by replacing diesel-powered mining vehicles and plant machinery with electric equivalents, and connecting sites to local grids to avoid onsite electricity generation. This approach has the potential to fully eliminate direct emissions at some mining sites where entire vehicle fleets can be electrified. Electrification is increasingly adopted across the sector, as documented by numerous mining companies. However, practical constraints—including the size of operations, the number of vehicles, charging capacity, costs, and limitations on vehicle range—may restrict the feasibility of complete adoption (Schmidt et al., 2025).

5.12 textiles-leather-apparel - Energy efficiency + heat pumps

The textile, leather, and apparel manufacturing sector generates significant greenhouse gas emissions primarily from energy-intensive processes such as fiber processing, dyeing, and leather tanning, which rely heavily on fossil fuels for heat production. Heat production constitutes over two-thirds of global industrial energy demand, with only a small portion derived from renewable sources. Emissions can be mitigated by improving energy efficiency and electrifying heat generation through industrial heat pumps, which lower operational energy consumption and reduce GHG emissions. While the adoption of heat pumps entails an initial capital investment, efficiency gains and reduced operational costs make them cost-effective over time. A 50% reduction in emissions has been assumed for this strategy, accounting for any increased emissions from electricity generation. Industrial heat pumps are currently being adopted in Chinese and Indian markets on a limited scale, with broader adoption expected by 2030 (Apparel Impact, 2025; Squarespace, 2025).

5.13 wood-and-wood-products - Energy from biomass

The production of wood and wood products generates greenhouse gas emissions primarily from fuel combustion in mill equipment and rolling stock, accounting for approximately 0.03% of global CO2-equivalent emissions. A practical approach to reducing these emissions is the use of excess forest residuals as biomass to replace fossil fuels in the production process. By utilizing these residuals for heat energy in mills, net emissions can be reduced by up to 66%. Some mills have already implemented the use of forest residues for power or heating, demonstrating feasibility, though wider adoption may be influenced by financial and technological constraints globally (Brandeis, 2024; FPJ, 2024).

5.14 enteric-fermentation-other - Feed additives in ruminant diet

Feed additives in ruminant diets offer a strategy to reduce methane emissions from enteric fermentation in non-cattle livestock, including sheep, goats, and yaks, which together account for approximately 1.2% of global greenhouse gas emissions. These additives are methane-inhibiting, suppressing the bacteria responsible for methane production in the digestive system, and thereby lowering emissions. Using compounds, such as 3-NOP, have shown emissions reductions of around 20% in enteric fermentation methane emissions.

Feed additives adoption has been implemented in various countries, including the EU, the U.S.A., and Brazil, primarily to enhance beef cattle weight gain or milk production, with reductions in methane emissions considered a secondary benefit. Despite this, global uptake remains limited due to regulatory restrictions in some regions, costs associated with implementation, potential impacts on product quality and prices, farmers' unfamiliarity with the technology, and consumer skepticism.

5.15 cropland-fires - Residue removal without burning

Crop residues are the leftover crop biomass remaining after harvest, such as straw or stover. Rather than burning these residues, the recommended approach is to remove them without combustion, which eliminates emissions associated with burning. This practice avoids the release of carbon dioxide, methane, and nitrous oxide that would otherwise result from the combustion of leftover crop residues.

In many agricultural contexts, crop residues have additional value as animal feed, bedding material, or organic soil amendments. In regions with diversified agricultural economies, established markets for these byproducts create economic incentives for adopting residue removal rather than burning. However, some farmers continue to burn crop residues due to time constraints associated with double cropping, as they need to clear fields quickly to plant the next crop. More mechanized agricultural systems are better equipped to manage residues efficiently, with the capacity to collect and transport them for alternative uses. The effectiveness of this approach therefore depends on the degree of mechanization, market access for residue byproducts, and timing pressures within local cropping systems.

Supplementary material

Table S1 Climate TRACE, EDGAR, and FAOSTAT Data defined by UNFCCC categories. Bolded sector codes indicate the sector partially covers that IPCC code.

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
FAOSTAT	Enteric Fermentation	3.A
FAOSTAT	Manure Management	3.B
FAOSTAT	Manure applied to Soils	3.D.1.b.i
FAOSTAT	Manure left on Pasture	3.D.1.b.ii
FAOSTAT	Synthetic Fertilizers	3.D.1.a
FAOSTAT	Rice Cultivation	3.C
FAOSTAT	Burning - Crop residues	3.F
FAOSTAT	Crop Residues	3.D.1.d
FAOSTAT	On-farm energy use	1.A.4.c
FAOSTAT	Savanna fires	3.E, 4.C.1
FAOSTAT	Fires in humid tropical forests	4.B.2.a, 4.C.2.a, 4.E.2.a, 4.A.1
FAOSTAT	Forest fires	4.B.2.a, 4.C.2.a, 4.E.2.a, 4.A.2
FAOSTAT	Fires in organic soils	
FAOSTAT	Drained organic soils	3.D.1.e, 3.D.1.f
FAOSTAT	Drained organic soils	3.D.1.e, 3.D.1.f
FAOSTAT	Net Forest conversion	
FAOSTAT	Forestland	4.A
EDGAR	Main Activity Electricity and Heat Production	1.A.1.a
EDGAR	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries	1.A.1.b, 1.A.1.c
EDGAR	Manufacturing Industries and Construction	1.A.2
EDGAR	Civil Aviation	1.A.3.a
EDGAR	Road Transportation no resuspension	1.A.3.b
EDGAR	Railways	1.A.3.c
EDGAR	Water-borne Navigation	1.A.3.d
EDGAR	Other Transportation	1.A.3.e
EDGAR	Other Sectors	1.A.4
EDGAR	Non-Specified	1.A.5
EDGAR	Solid Fuels	1.B.1
EDGAR	Oil and Natural Gas	1.B.2
EDGAR	Cement production	2.A.1
EDGAR	Lime production	2.A.2
EDGAR	Glass Production	2.A.3
EDGAR	Other Process Uses of Carbonates	2.A.4

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
EDGAR	Chemical Industry	2.B
EDGAR	Metal Industry	2.C
EDGAR	Non-Energy Products from Fuels and Solvent Use	2.D
EDGAR	Liming	3.G
EDGAR	Urea application	3.H
EDGAR	Other	3.J
EDGAR	Enteric Fermentation	3.A
EDGAR	Manure Management	3.B
EDGAR	Emissions from biomass burning	3.E, 3.F, **4.A.1.c, 4.C.1.a, 4.D.1.b**
EDGAR	Rice cultivations	3.C
EDGAR	Solid Waste Disposal	5.A
EDGAR	Biological Treatment of Solid Waste	5.B
EDGAR	Incineration and Open Burning of Waste	5.C
EDGAR	Wastewater Treatment and Discharge	5.D
EDGAR	Other	5.E
EDGAR	Direct N2O Emissions from managed soils	3.D.1
EDGAR	Indirect N2O Emissions from managed soils	3.D.2
EDGAR	Indirect N2O Emissions from manure management	
EDGAR	Indirect N2O emissions from the atmospheric deposition of nitrogen in NOx and NH3	3.D.2.a
EDGAR	Other	6
CEDS	1A1a_Electricity-autoproducer	1.A.1.a.i
CEDS	1A1a_Electricity-public	1.A.1.a.i
CEDS	1A1a_Heat-production	1.A.1.a.iii
CEDS	1A1bc_Other-transformation	1.A.1.b, 1.A.1.c
CEDS	, 1A5_Other-unspecified	1.A.5
CEDS	1B1_Fugitive-solid-fuels	1.B.1
CEDS	1B2_Fugitive-petr	1.B.2
CEDS	1B2b_Fugitive-NG-prod	1.B.2.b
CEDS	1B2d_Fugitive-other-energy	1.B.2.d
CEDS	1B2b_Fugitive-NG-distr	1.B.2.b
CEDS	2A1_Cement-production	2.A.1
CEDS	1A2a_Ind-Comb-Iron-steel	1.A.2.a
CEDS	2C1_Iron-steel-alloy-prod	2.C.1
CEDS	1A2b_Ind-Comb-Non-ferrous-metals,	1.A.2.b
CEDS	2C3_Aluminum-production	2.C.3
CEDS	2C4_Non-Ferrous-other-metals	2.C.4
CEDS	1A2c_Ind-Comb-Chemicals,,	1.A.2.c
CEDS	2B_Chemical-industry	2.B

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
CEDS	2B2_Chemicals-Nitric-acid	2.B.2
CEDS	2B3_Chemicals-Adipic-acid	2.B.3
CEDS	1A2d_Ind-Comb-Pulp-paper	1.A.2.d
CEDS	1A2g_Ind-Comb-mining-quarying	1.A.2.g.iii
CEDS	1A2e_Ind-Comb-Food-tobacco	2.A.2.e
CEDS	1A2g_Ind-Comb-textile-leather	**1.A.2.g.vi**
CEDS	1A2g_Ind-Comb-wood-products	**1.A.2.g.iv**
CEDS	2A2_Lime-production	2.A.2
CEDS	2Ax_Other-minerals	2.A.3, 2.A.4
CEDS	1A2f_Ind-Comb-Non-metalic-minerals	1.A.2.f
CEDS	1A2g_Ind-Comb-Construction	1.A.2.g.v
CEDS	1A2g_Ind-Comb-machinery	1.A.2.g.i
CEDS	1A2g_Ind-Comb-other	1.A.2.g.viii
CEDS	1A2g_Ind-Comb-transpequip	1.A.2.g.ii
CEDS	2D_Chemical-products-manufacture-processing,	2.D
CEDS	2D_Other-product-use	2.D.3.d
CEDS	2D_Degreasing-Cleaning,	2.D.3
CEDS	2D_Paint-application,	2.D.3
CEDS	2H_Pulp-and-paper-food-beverage-wood	2.H
CEDS	1A3aii_Domestic-aviation	1.A.3.a
CEDS	1A3ai_International-aviation	
CEDS	1A3dii_Domestic-navigation	1.A.3.d
CEDS	1A3di_International-shipping	
CEDS	1A3di_Oil_Tanker_Loading	1.A.3.d
CEDS	1A3b_Road	1.A.3.b
CEDS	1A3c_Rail	1.A.3.c
CEDS	1A3eii_Other-transp	1.A.3.e
CEDS	1A4b_Residential	1.A.4.b
CEDS	1A4a_Commercial-institutional	1.A.4.a
CEDS	1A4c_Agriculture-forestry-fishing	1.A.4.c
CEDS	3E_Enteric-fermentation	3.A
CEDS	3B_Manure-management	3.B
CEDS	3D_Rice-Cultivation	3.C
CEDS	3D_Soil-emissions	3.D
CEDS	3I_Agriculture-other	3.I
CEDS	7BC_Indirect-N2O-non-agricultural-N	
CEDS	5A_Solid-waste-disposal	5.A

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
CEDS	5E_Other-waste-handling	5.E
CEDS	5C_Waste-combustion	5.C
CEDS	5D_Wastewater-handling	5.D
ClimateTRACE	electricity-generation	1.A.1.a.i, 1.A.1.a.ii
ClimateTRACE	heat-plants	1.A.1.a.iii
ClimateTRACE	other-energy-use	1.A.1.a.iv
ClimateTRACE	domestic-aviation	1.A.3.a
ClimateTRACE	international-aviation	7.A
ClimateTRACE	road-transportation	1.A.3.b
ClimateTRACE	railways	1.A.3.c
ClimateTRACE	international-shipping	7.B
ClimateTRACE	domestic-shipping	1.A.3.d
ClimateTRACE	other-transport	1.A.3.e
ClimateTRACE	residential-onsite-fuel-usage	1.A.4.b.i
ClimateTRACE	non-residential-onsite-fuel-usage	1.A.4.a.i
ClimateTRACE	other-onsite-fuel-usage	1.A.4.a.ii, 1.A.4.a.iii, 1.A.4.b.ii, 1.A.4.b.iii, 1.A.4.c
ClimateTRACE	coal-mining	1.B.1.a
ClimateTRACE	other-solid-fuels	1.B.1.b, 1.B.1.c
ClimateTRACE	oil-and-gas-production	1.A.1.c.ii, 1.B.2.a.i, 1.B.2.a.ii, 1.B.2.b.i, 1.B.1.b.ii, 1.B.1.b.iii, 1.B.2.c
ClimateTRACE	oil-and-gas-transport	1.B.2.a.iii, 1.B.2.b.iv
ClimateTRACE	oil-and-gas-refining	1.A.1.b, 1.B.2.a.iv, 1.B.2.a.v, 1.B.2.b.v
ClimateTRACE	other-fossil-fuel-operations	1.B.2.a.vi, 1.B.2.b.vi, 1.B.2.d
ClimateTRACE	cement	**1.A.2.f**, 2.A.1
ClimateTRACE	chemicals	**1.A.2.c**, 2.B.1, 2.B.7, 2.B.8.a
ClimateTRACE	petrochemicals-steam-cracking	2.B.8.b
ClimateTRACE	other-chemicals	2.B.2, 2.B.3, 2.B.4, 2.B.5, 2.B.6, 2.B.8.c, 2.B.8.e, 2.B.8.f, 2.B.8.g
ClimateTRACE	iron-and-steel	1.A.2.a, 2.C.1
ClimateTRACE	aluminum	**1.A.2.b**, 2.C.3
ClimateTRACE	other-metals	**1.A.2.b**, 2.C.2, 2.C.4, 2.C.5, 2.C.6, 2.C.7
ClimateTRACE	pulp-and-paper	1.A.2.d
ClimateTRACE	glass	2.A.3
ClimateTRACE	lime	2.A.2
ClimateTRACE	food-beverage-tobacco	1.A.2.e, 2.H.1
ClimateTRACE	wood-and-wood-products	1.A.2.g.iv

Data Source	Original Inventory Sector Name	UNFCCC CRF 2006 Category
ClimateTRACE	textiles-leather-apparel	1.A.2.g.vi
ClimateTRACE	other-manufacturing	**1.A.2.f**, 1.A.2.g.i, 1.A.2.g.ii, 1.A.2.g.v, 1.A.2.g.vii, 1.A.2.g.viii, 2.A.4, 2.D, 2.G
ClimateTRACE	bauxite-mining	1.A.2.g.iii
ClimateTRACE	copper-mining	1.A.2.g.iii
ClimateTRACE	iron-mining	1.A.2.g.iii
ClimateTRACE	rock-quarrying	1.A.2.g.iii
ClimateTRACE	sand-quarrying	1.A.2.g.iii
ClimateTRACE	other-mining-and-quarrying	1.A.2.g.iii
ClimateTRACE	enteric-fermentation-cattle-operation	3.A.1
ClimateTRACE	enteric-fermentation-cattle-pasture	3.A.1
ClimateTRACE	enteric-fermentation-other	3.A.2, 3.A.3, 3.A.4
ClimateTRACE	manure-management-cattle-operation	3.B.1
ClimateTRACE	manure-left-on-pasture-cattle	3.B.1, 3.D.1.c
ClimateTRACE	manure-management-other	3.B.2, 3.B.3, 3.B.3
ClimateTRACE	rice-cultivation	3.C
ClimateTRACE	synthetic-fertilizer-application	3.D.1.a
ClimateTRACE	crop-residues	3.D.1.d
ClimateTRACE	manure-applied-to-soils	3.D.1.b, 3.D.1.c
ClimateTRACE	cropland-fires	3.F
ClimateTRACE	other-agricultural-soil-emissions	3.D.1.g, 3.D.2, 3.G, 3.H, 3.I, 3.J
ClimateTRACE	solid-waste-disposal	5.A
ClimateTRACE	biological-treatment-of-solid-waste-and-biogenic	5.B
ClimateTRACE	incineration-and-open-burning-of-waste	5.C
ClimateTRACE	industrial-wastewater-treatment-and-discharge	5.D.2
ClimateTRACE	domestic-wastewater-treatment-and-discharge	5.D.1
ClimateTRACE	fluorinated-gases	2.B.9, 2.F
ClimateTRACE	forest-land-fires	4.A
ClimateTRACE	forest-land-clearing	4.A
ClimateTRACE	forest-land-degradation	4.A
ClimateTRACE	net-forest-land	4.A
ClimateTRACE	net-shrubgrass	4.C, 3.E
ClimateTRACE	net-wetland	4.D.1.a, 4.D.1.c, 4.D.2
ClimateTRACE	shrub grass-fires	4.C, 3.E
ClimateTRACE	wetland-fires	4.D.1.a, 4.D.1.c, 4.D.2
ClimateTRACE	removals	
ClimateTRACE	water-reservoirs	4.D.1.b

Table S2 The crosswalk table: Climate TRACE sector and related source data

Sector on Climate TRACE site	Equation to calculate	Gas	Filled data source
Other Energy Use	= EDGAR[“Main Activity Electricity and Heat Production”] - ClimateTrace[“electricity-generation”] - ClimateTrace[“heat-plants”]	CO_2 CH_4 N_2O	EDGAR 2024
Railways	= EDGAR[“Railways”]	CO_2 CH_4 N_2O	EDGAR 2024
Other Transport	= EDGAR[“Other Transportation”]	CO_2 CH_4 N_2O	EDGAR 2024
Other Onsite Fuel Usage	= EDGAR[“Non-Specified”]	CO_2 CH_4 N_2O	EDGAR 2024
Other Solid Fuels	= EDGAR[“Solid Fuels”] - ClimateTrace[“coal-mining”]	CO_2 CH_4 N_2O	EDGAR 2024
Other Fossil Fuel Operations	= EDGAR[“Oil and Natural Gas”] + EDGAR[“Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries”] - ClimateTrace[“oil-and-gas-production”] - ClimateTrace[“oil-and-gas-transport”] - ClimateTrace[“oil-and-gas-refining”]	CO_2 CH_4 N_2O	EDGAR 2024
Other Manufacturing	= CEDS[“Construction Combustion”] + CEDS[“Machinery Combustion”] + CEDS[“Transportation Equipment Combustion”] + CEDS[“Other Combustion”] + CEDS[“Other Minerals”] + CEDS[“Chemical Products Manufacturing and Processing”] + CEDS[“Degreasing and Cleaning”] + CEDS[“Other Product Use”] + CEDS[“Paint Application”] + “Misc. Mineral Industry Combustion” (see Section 2.2.2.1) - EDGAR[“Glass Production”]	CO_2 CH_4 N_2O	CEDS EDGAR 2024
Enteric Fermentation Other	=FAOSTAT[“enteric-fermentation- non	CH_4	FAOSTAT

Sector on Climate TRACE site	Equation to calculate	Gas	Filled data source
	cattle"]		
Manure Management Other	=FAOSTAT["manure-management- non cattle"]	CH_4	FAOSTAT
Other Agricultural Soil Emissions	=FAOSTAT["manure-left-on-pasture - noncattle"] + FAOSTAT["drained-organic-soils"]+ EDGAR["Liming"] + EDGAR["Urea application"]	CO_2 N_2O	FAOSTAT
Other Agricultural Soil Emissions	=FAOSTAT["crop residues"] + EDGAR["Liming"] + EDGAR["Urea application"]	CH_4	FAOSTAT
Biological Treatment of Solid Waste and Biogenic	= EDGAR["Biological Treatment of Solid Waste"]	CO_2 CH_4 N_2O	EDGAR 2024
Incineration and Open Burning of Waste	= EDGAR["Incineration and Open Burning of Waste"]	CO_2 CH_4 N_2O	EDGAR 2024
Fluorinated Gases	= EDGAR[fluorinated-gases]	f-gases	EDGAR 2024
Other Mining and Quarrying	= CEDS["mining & quarrying combustion"] - ClimateTRACE["copper-mining"] - ClimateTRACE["bauxite-mining"] - ClimateTRACE["iron-mining"] - ClimateTRACE["rock-quarrying"] - ClimateTRACE["sand-quarrying"]	CO_2 CH_4 N_2O	CEDS
Other Chemicals	= EDGAR["Chemical Industry"] + CEDS["Chemical Industry Combustion"] - ClimateTRACE["chemicals"] - ClimateTRACE["petrochemicals-steam-cracking"]	CO_2 CH_4 N_2O	EDGAR 2024 CEDS
Wood and Wood Products	= CEDS["Wood, wood products combustion"]	CO_2 CH_4 N_2O	CEDS
Other Metals	= EDGAR["Metal Industry"] + CEDS["Non-Ferrous metals combustion"] + CEDS["Iron and steel combustion"]- ClimateTRACE["iron-and-steel"] ClimateTRACE["aluminum"]	CO_2 CH_4 N_2O	EDGAR 2024 CEDS

Table S3 Climate TRACE sectors with IPCC equivalent sector coverage. Sector specific global emission contributions (based on Annex 1) to the 2024 global total excluding LULUCF sectors, estimation method (from Introduction), data sources to generate emission estimates are provided.

Sector	Subsector	IPCC Category	% of Global Emissions w/o LULUCF (Based on CT inventory)	Estimation Method	Data Source
power	electricity-generation	1.A.1.a.i Electricity Generation 1.A.1.a.ii Combined Heat and Power Generation	22.0%	1	WattTime, Transition Zero, Global Energy Monitor
power	heat-plants	1.A.1.a.iii	0.15%	3	WattTime
power	other-energy-use	1.A.1.a.iii Heat Plants 1.A.1.a.iv Other	3.45%	5	EDGAR
buildings	residential-onsite-fuel-usage	1.A.4.b.i Residential Stationary Combustion	5.45%	2	Duke University
buildings	non-residential-onsite-fuel-usage	1.A.4.a.i Commercial/institutional Stationary Combustion	0.74%	2	Duke University
buildings	other-onsite-fuel-usage	1.A.5 Non-Specified	0.33%	5	EDGAR
manufacturing	petrochemical-steam-cracking	2.B.8.b Ethylene	0.49%	3	RMI
manufacturing	iron-and-steel	1.A.2.a Iron and Steel 2.C.1 Iron and Steel Production	4.51%	1	Transition Zero
manufacturing	cement	1.A.2.f Non-metallic Minerals 2.A.1 Cement Production	3.73%	1	Transition Zero
manufacturing	chemicals	1.A.2.c Manufacture of Solid Fuels and Other Energy Industries 2.B.1 Ammonia Production 2.B.7 Soda Ash Production 2.B.8.a Methanol	0.98%	3	Transition Zero
manufacturing	aluminum	1.A.2.b Non-Ferrous Metals 2.C.3 Aluminum Production	0.70%	3	Transition Zero
manufacturing	pulp-and-paper	1.A.2.d Pulp, Paper and Print 2.H.1 Pulp and Paper	0.21%	3	Transition Zero
manufacturing	glass	2.A.3 Glass production	0.07%	4	WattTime
manufacturing	lime	2.A.2 Lime Production	0.88%	4	WattTime
manufacturing	food-beverage-tobacco	1.A.2.e Food Processing, Beverages and Tobacco 2.H.2 Food and Beverages Industry	0.45%	4	WattTime
manufacturing	wood-and-wood-products	1.A.2.g.iv Wood and Wood Products	0.02%	5	WattTime
manufacturing	textiles-leather-apparel	1.A.2.g.vi Textile and Leather	0.08%	4	WattTime
manufacturing	other-metals	2.C.2 Ferroalloys Production 2.C.4 Magnesium Production 2.C.5 Lead Production 2.C.6 Zinc Production 2.C.7 Other	0.30%	5	WattTime
manufacturing	other-chemicals	2.B.2 Nitric Acid Production 2.B.3 Adipic Acid Production	1.29%	5	WattTime

Sector	Subsector	IPCC Category	% of Global Emissions w/o LULUCF (Based on CT inventory)	Estimation Method	Data Source
		2.B.4 Caprolactam, Glyoxal and Glyoxylic Acid Production 2.B.5 Carbide Production 2.B.6 Titanium Dioxide Production 2.B.8.c Ethylene Dichloride and Vinyl Chloride Monomer 2.B.8.d Ethylene Oxide 2.B.8.e Acrylonitrile 2.B.8.f Carbon Black 2.B.8.g Other			
manufacturing	other-manufacturing	1.A.2.g.i Manufacturing of Machinery 1.A.2.g.ii Manufacturing of Transport Equipment 1.A.2.g.v Construction 1.A.2.g.vii Off-road Vehicles and Other Machinery 1.A.2.g.viii Other 2.A.4 Other Process Uses of Carbonates 2.D Non-energy Products from Fuels and Solvent Use 2.G Other Product Manufacture and Use	3.10%	5	EDGAR
fossil-fuel-operations	oil-and-gas-refining	1.A.1.b Petroleum Refining 1.B.2.a.iv Oil Refining / Storage 1.B.2.a.v Oil Distribution of Oil Products 1.B.2.b.v Natural Gas Distribution	1.60%	3	RMI
fossil-fuel-operations	oil-and-gas-production	1.A.1.c.ii Oil and Gas Extraction 1.B.2.a.i Exploration 1.B.2.a.ii Production 1.B.2.b.i Exploration 1.B.2.b.ii Production 1.B.2.b.iii Processing 1.B.2.c Venting and Flaring	6.47%	2	
fossil-fuel-operations	oil-and-gas-transport	1.B.2.a.iii Transport 1.B.2.b.iv Transmission and Storage	2.59%	2	RMI
fossil-fuel-operations	other-solid-fuels	1.B.1.b Solid Fuel Transformation 1.B.2.c Other	1.18%	5	EDGAR
fossil-fuel-operations	coal-mining	1.B.1.a Coal Mining and Handling	3.46%	3	WattTime, Global Energy Monitor
fossil-fuel-operations	other-fossil-fuel-operations	1.A.1.c Manufacture of Solid Fuels and Other Energy Industries 1.B.2.a.vi Refining / Storage 1.B.2.b.vi Other 1.B.2.d Other	0.48%	4	WattTime analysis of RMI and EDGAR data
mineral-extraction	copper-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.21%	3	Hypervine

Sector	Subsector	IPCC Category	% of Global Emissions w/o LULUCF (Based on CT inventory)	Estimation Method	Data Source
mineral-extraction	iron-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.16%	3	Hypervine
mineral-extraction	bauxite-mining	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.02%	3	Hypervine
mineral-extraction	sand-quarrying	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.001%	3	Hypervine
mineral-extraction	rock-quarrying	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.002%	3	Hypervine
mineral-extraction	other-mining-quarrying	1.A.2.g.iii Mining (Excluding Fuels) and Quarrying	0.05%	5	CEDS
transportation	domestic-aviation	1.A.3.a Domestic Aviation	0.52%	3	WattTime
transportation	international-aviation	7.A International Aviation	0.941%	3	WattTime
transportation	road-transportation	1.A.3.b Road Transportation	10.88%	1	Johns Hopkins University Applied Physics Laboratory
transportation	domestic-shipping	1.A.3.d. Domestic Navigation	0.78%	2	OceanMind, Global Fishing Watch
transportation	international-shipping	7.B International Navigation	0.98%	2	OceanMind, Global Fishing Watch
transportation	railways	1.A.3.c Railways	0.17%	5	EDGAR
transportation	other-transport	1.A.3.e Other Transportation	0.29%	5	EDGAR
agriculture	rice-cultivation	3.C Rice Cultivation	1.08%	2	University of Malaysia Terengganu
agriculture	cropland-fires	3.F Field Burning of Agricultural Residues	2.25%	2	EDGAR
agriculture	enteric-fermentation-cattle-operations	3.A.1 Cattle	1.93%	2	WattTime
agriculture	enteric-fermentation-cattle-pasture	3.A.1 Cattle	2.49%	2	Johns Hopkins Applied Physics Laboratory
agriculture	enteric-fermentation-other	3.A.2 Sheep, 3.A.3 Swine, 3.A.4 Other	1.28%	5	WattTime analysis of FAOSTAT data
agriculture	manure-management-cattle-operations	3.B.1 Cattle	0.33%	2	WattTime
agriculture	manure-left-on-pasture	3.B.1, 3.D.1.c. Urine and Dung Deposited by Grazing Animals	0.76%	2	Johns Hopkins Applied Physics Laboratory
agriculture	manure-management-other	3.B.2 Sheep, 3.B.3 Swine, 3.B.3 Other	0.36%	5	WattTime analysis of FAOSTAT data
agriculture	synthetic-fertilizer-application	3.D.1.a Inorganic N Fertilizers, 3.D.2 Indirect N_2O Emissions From Managed Soils	0.80%	3	Michigan State University

Sector	Subsector	IPCC Category	% of Global Emissions w/o LULUCF (Based on CT inventory)	Estimation Method	Data Source
agriculture	crop-residues	3.D.1.d Crop Residues	0.20%	5	FAOSTAT
agriculture	manure-applied-to-soils	3.D.1.b.i Animal Manure Applied to Soils	0.23%	5	FAOSTAT
agriculture	other-agricultural-soil-emissions	3.D.1.e Mineralization/Immobilization Associated with Loss/Gain of Soil Organic Matter 3.D.1.f Cultivation of Organic Soils 3.D.1.g Other 3.G Liming 3.H Urea Application	2.25%	5	FAOSTAT and EDGAR
waste	solid-waste-disposal	5.A Solid Waste Disposal	1.73%	2 (source) 5 (country)	WattTime (source) EDGAR (country)
waste	biological-treatment-of-solid-waste-&-biogenic	5.B Biological Treatment of Solid Waste	0.04%	5	EDGAR
waste	incineration-and-open-burning-of-waste	5.C Incineration and Open Burning of Waste	0.11%	5	EDGAR
waste	domestic-wastewater-treatment-and-discharge	5.D.1 Domestic Wastewater Treatment and Discharge	1.22%	2	Johns Hopkins Applied Physics Laboratory
waste	industrial-wastewater-treatment-and-discharge	5.D.2 Industrial Wastewater Treatment and Discharge	0.27%	2	Johns Hopkins Applied Physics Laboratory
fluorinated-gasses	fluorinated-gasses	2.B Chemical Industry (HFCs and PFCs) 2.C Metal Industry (HFCs and PFCs) 2.E Electronics Industry (HFCs and PFCs) 2.F Product Uses as Substitutes for Ozone Depleting Substances (HFCs and PFCs) 2.G Other Product Manufacture and Use (HFCs and PFCs)	2.67%	5	EDGAR

Sector	Subsector	IPCC Category	% of Global Emissions w/o LULUCF (Based on CT inventory)	Estimation Method	Data Source
forestry-and-land-use	water-reservoirs	4.D.1.b Flooded Land Remaining Flooded Land	0.05%	2	Johns Hopkins Applied Physics Laboratory
forestry-and-land-use	net-forest	4.A Forest Land	0%	1	CTrees
forestry-and-land-use	net-shrubgrass	4.C Grassland	0%	1	CTrees
forestry-and-land-use	net-wetland	4.D.1.a Peat Extraction Remaining Peat Extraction, 4.D.1.c Other Wetlands Remaining Other Wetlands, 4.D.2. Land Converted to Wetlands	0%	1	CTrees

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Geographic boundaries and names (iso3_country data attribute): The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on Climate TRACE are generated from the Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) along with their corresponding ISO3 codes, and with the following adaptations:

- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code 'XKX';
- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based on the extent of their territorial waters;
- XAD (Akrotiri and Dhekelia), XCL (Clipperton Island), XPI (Paracel Islands) and XSP (Spratly Islands) are not included in the Climate TRACE dataset;
- ZNC name changed to 'Turkish Republic of Northern Cyprus' at GADM level 0;
- The borders between India, Pakistan and China have been assigned to these countries based on GADM codes Z01 to Z09.
- Two IDs have been created for a region in UKR with missing IDs (at Level 1 and Level

2).

- UNK added to GADM level 0 to denote 'unknown' countries, which primarily applies to non-broadcasting-vessels whose port berthing locations are not known.
- TUR name changed to “Türkiye”
- SWZ name changed to “Eswatini”
- Missing Con Dao Island added as VNM.7.X_1 and Kili Island added as MHL.X_1.

The above usage is not warranted to be error free and does not imply the expression of any opinion whatsoever on the part of Climate TRACE Coalition and its partners concerning the legal status of any country, area or territory or of its authorities, or concerning the delimitation of its borders.

Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

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