Non-Greenhouse Gas Emissions Estimates Across Sectors

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1. Introduction

The World Health Organization (WHO) estimates that globally 6.7 million premature deaths annually are caused by poor air quality, with 4.2 million of those deaths caused by ambient outdoor air pollution [1]. Whereas the impacts from releasing greenhouse gasses (GHGs) are long term, air pollution can have both long-term and immediate impacts on the health of individuals and communities. Further, anthropogenic sources of air pollutants are also an issue of climate justice as the impacts of air pollution are disproportionately felt by poorer, disadvantaged communities and the Global South.

Currently there are gaps in the knowledge of the sources and magnitude of ambient air pollution, and these gaps are a major impediment to addressing critical health and environmental problems. While there are many datasets that focus on air pollution used by researchers, there is no air pollution dataset that has facility-specific emissions, global coverage, and high recency. These characteristics are necessary for direct accountability of polluters, for policy and decision-makers to regulate pollutants and improve public health more efficiently, and for activists to direct action effectively. This document describes Climate TRACE's initial efforts to fill this monitoring gap by applying their knowledge of and approaches for estimating greenhouse gas sources to air pollution.

2. Data and Methods

2.1. Overview

Estimates of emissions that take a bottom-up approach (where emissions are estimated by accounting for different consumption, energy-demand, and other activities) often lack facility-level specificity that is required for identifying polluters and holding them accountable. This includes the high-quality Emissions Dataset for Atmospheric Research (EDGAR) and the mosaic Community Emissions Data System (CEDS) which use sophisticated and granular approaches to estimating emissions and mitigation controls for country-level emissions estimates but rely on proxies for distributing emissions spatially [2,3,4]. The approach described here leverages these emissions inventories in order to provide conversion factors between greenhouse gas emissions and pollution emissions for a given facility.

These co-pollutant conversion factors are used in place of Climate TRACE sectors that do not directly report facility-level estimates. The approach assumes a linear relationship between emissions of GHGs and non-GHGs, i.e. for every X tonnes of greenhouse gas emitted, Y tonnes of pollutant is emitted. This method was chosen as co-pollutant ratios are of high interest for climatologists as they can provide insight to the anthropogenic processes of a region [5]. These ratios are estimated at a country-sector-fuel level, and then applied across Climate TRACE assets – essentially utilizing CEDS/EDGAR emissions estimates but rescaled and distributed based on Climate TRACE data.

Various improvements were made between Phase 6 and Phase 7 of Climate TRACE air pollutants in order to more accurately estimate emissions. First, facility-level emissions for several sectors are broken up into combustion and non-combustion/process-related emissions rather than just a composite emission function which allows for more precise estimates of emissions arising from these components. Broadly speaking, the distinction between combustion and process-related emissions is akin to their separation into the UNFCCC 1 and 2 emissions groups. Second, a harmonic average between CEDS and EDGAR is used to compute emissions ratios which improves emissions estimates by reducing the error induced by the ratio computation in some sectors and assimilating the bias in others (*see Section 2.4*). Lastly, previously unaccounted for emissions from mining are now built into their emissions model.

2.2. Data

CEDS and EDGAR air pollution emissions estimates are used for predicting the air pollution emissions for Climate TRACE assets. A mapping of CEDS and EDGAR sectors (which are IPCC code-based) to Climate TRACE sectors is needed for making this estimate and is shown in Table 2 and Table 3 in Supplementary Materials. In addition, as CEDS and EDGAR only estimate emissions up to 2022, forward filling is used for any year after.

Countries are matched according to ISO3 codes. CEDS does not provide estimates for 31 countries/territories that are available in Climate TRACE. Many of these are small island nations or territories, so proxy estimates are provided based on similar nearby countries or sovereign states (see Table 4 in the supplemental).

2.3. Estimation Approach

As Climate TRACE estimates emissions at the facility-level, multiple sources of emissions at a given facility are combined to form a single estimate. As a generalization, the emissions Em from a facility a of gas g are modeled as arising from combustion-related emissions $Em^{g}_{a,comb}$ and process-related emissions $Em^{g}_{a,proc}$, expressed by:

$$Em^{g}_{a} = Em^{g}_{a,comb} + Em^{g}_{a,proc} \text{ (Eq. 1).}$$

These emissions are estimated using a bottom-up approach wherein activities for these emissions are modeled and multiplied by corresponding emissions factors:

$$Em_{a}^{g} = A_{a,comb} \cdot EF_{a,comb}^{g} + A_{a,proc} \cdot EF_{a,proc}^{g} \text{ (Eq 2).}$$

For non-GHGs, emissions factors for combustion and process are dependent on asset-level pollution controls; and many sectors have asset-level pollution control data needed for determining these emissions factors. However, for other sectors and many regions globally, pollution control data is difficult to access; hence these emissions factors have to be estimated. To do so, national-level emissions factors are estimated using a fusion of emissions estimates from EDGAR and CEDS. Primarily, co-pollutant ratios (r) are developed such that CO_2 equivalent values can be translated to pollution values with:

$$Em_{a}^{g} = r_{comb}^{g} \cdot Em_{a,comb}^{CO2eq} + r_{proc}^{g} \cdot Em_{a,proc}^{CO2eq} \text{ (Eq. 3),}$$

where

$$r_{comb/proc}^{g} = \frac{Em_{a,comb/proc}^{g}}{Em_{a,comb/proc}^{CO2eq}} \text{ (Eq. 4).}$$

In the previous phase, these ratios were estimated purely from either EDGAR or CEDS for a given sector (s) and country (c); however, to improve upon national-level estimates a harmonic average is used to mix ratios arising from these datasets – expressed for the combustion fraction with:

$$r_{comb}^{g} \approx r_{s,c,comb}^{g,\,EDGAR/CEDS} = \frac{2}{\left(r_{s,c,comb}^{g,EDGAR}\right)^{-1} + \left(r_{s,c,comb}^{g,CEDS}\right)^{-1}} \text{ (Eq. 5),}$$

with $r_{s,c,comb}^{g,EDGAR}$ and $r_{s,c,comb}^{g,CEDS}$ defined with Equation 4 using EDGAR and CEDS, respectively. A similar expression is used for the process ratio. Section 2.4 discusses how using this approach reduces bias in the model.

The outcome of this approach, although having uniform emissions factors across all facilities from the same sector and in the same nation, is that the estimated national pollution estimate is conserved and distributed based on facility-level activity and location directly as opposed to spatial proxies. In addition, the use of CO_2 equivalent – a weighted sum of GHG species based on their heat absorption compared to CO_2 – allows for this analysis to be applied to sectors where different GHG species are dominant and others are negligible.

Carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), sulfur dioxide (SO_2), particulate matter smaller than 2.5 microns ($PM_{2.5}$), and speciated components of $PM_{2.5}$ that are byproducts of combustion – black carbon (BC) and organic carbon (OC) – were estimated in this manner and for all sectors where asset-level emissions were not directly estimated. For some sectors, particulate matter smaller than 10 microns (PM_{10}) was also estimated.

An additional conversion step was needed to produce $PM_{2.5}$ and PM_{10} estimates from CEDS as it only provides estimates of the speciated BC and OC pollutants. It is assumed that the mitigation of BC is equally effective for mitigating $PM_{2.5}$ since BC is a subspecies of $PM_{2.5}$. Thus, a conversion of CEDS BC emissions to $PM_{2.5}$ emissions can be made with:

$$Em_a^{PM2.5,CEDS} = \rho_{BC} \cdot Em_a^{BC,CEDS}, \text{ (Eq. 6)},$$

where $\rho_{BC} = \frac{1}{\%\ of\ PM2.5\ that\ is\ BC}$, or the ratio of the percent of $PM_{2.5}$ that is BC. A conversion from $PM_{2.5}$ emissions to PM_{10} emissions is made with a similar expression:

$$Em_a^{PM10,CEDS} = \rho_{PM10} \cdot Em_a^{PM2.5,CEDS} \text{ (Eq. 7)}.$$

The value of ρ_{BC} and ρ_{PM10} is computed for most sectors with the EMEP/EEA Air Pollutant Emission Inventory Guidebook [6], with the only exception being aviation where EPA Smartway is used [7]. For sectors where these values are unavailable in these resources an estimation is made with EDGAR, defined with:

$$\rho_{BC} \approx \frac{Em_{s,c}^{PM2.5,EGDAR}}{Em_{s,c}^{BC,EGDAR}}$$

and

$$\rho_{PM10} \approx \frac{Em_{s,c}^{PM10,EGDAR}}{Em_{s,c}^{PM2.5,EGDAR}}.$$

The generalization used with Equations 2 and 3 work well for most sectors, and even with sectors which lack either combustion or process emissions – e.g. the combustion only textile industry or the process only enteric fermentation. However, all mining assets required special treatment related to the process component of the emissions due to the asset lacking GHG emissions from process related activities (e.g. blasting of rock). Conveniently, Tier 1 emissions factors from [6] can be used directly with the activities in these sectors to produce process-related emissions, resulting in:

$$Em_a^g = r_{comb}^g \cdot Em_{a,comb}^{CO2eq} + A_{a,proc} \cdot EF_{a,proc}^g, \text{ (Eq. 8)}$$

which is used for producing proper $PM_{2.5}$ and PM_{10} values for all mining assets and NMVOC values for coal mines.

At this point cement, glass, and lime, are the only sectors which disaggregate combustion and process emissions. All remaining sectors – which include many industrial and waste sectors –

require a coarser approach for estimating emissions which produces an emissions ratio that produces a co-pollutant ratio that is a combination of the two. For these sectors, emissions are estimated with:

$$Em_{a}^{g} = r^{g}_{comb+proc} \cdot Em^{CO2eq}_{a,comb+proc}, \text{ (Eq.9)}$$

where

$$r^{g}_{comb+proc} = \frac{Em^{CO2eq}_{a,comb+proc}}{Em^{g}_{a,comb+proc}} \text{ (Eq. 10)}$$

and

$$Em^{g}_{a,comb+proc} = Em^{g}_{a,comb} + Em^{g}_{a,proc}. \text{ (Eq. 11)}$$

The ratio in Equation 10 is estimated by:

$$r^{g}_{comb+proc} \approx r^{g,\,EDGAR/CEDS}_{s,c,comb+proc} = \frac{2}{\left(r^{g,EDGAR}_{s,c,comb+proc}\right)^{-1} + \left(r^{g,CEDS}_{s,c,comb+proc}\right)^{-1}},$$

where $r^{g,EDGAR}_{s,c,comb+proc}$ and $r^{g,CEDS}_{s,c,comb+proc}$ are defined similarly to Equation 11.

After all emissions estimates are produced, gap-filling of zero and NaN emissions ratios is performed by replacing said values with the median of the non-zero/non-NaN values. At the time of this document, EDGAR's latest year for emissions estimates is 2022, and hence all years thereafter are estimates with the ratio in 2022.

2.4. Harmonic Mean of Ratio Error Analysis

The use of a harmonic average reduces the biases caused by either individual dataset. Consider only one emissions co-pollutant ratio which differs from the "true" conversion ratio (ρ) with some error ϵ, such that:

$$r_{1} = \rho\left(1 + \epsilon_{1}\right), \text{ (Eq. 12)},$$

for inventory 1 (e.g. CEDS) and similarly defined for inventory 2 (e.g. EDGAR). The relative error between the estimated emissions and the true emissions can be shown to be ϵ_{i}, with:

$$Em_{true} = \rho \cdot Em^{CO2e},$$

$$Em^{1}_{estimated} = r_{1} \cdot Em^{CO2e} = \rho\left(1 + \epsilon_{1}\right) \cdot Em^{CO2e},$$

$$\Rightarrow \frac{E^{1}_{estimated} - E_{true}}{E_{true}} = \epsilon_1 \text{ (Eq 7).}$$

Hence, for a single inventory, the discrepancy between the inventory and the true co-pollutant ratio is directly proportional to the error of the emissions estimate. Now consider using two emissions ratios that are combined with a harmonic mean such that the emissions estimate is:

$$Em^{harmonic}_{estimated} = r^{harmonic} \cdot Em^{CO2e}, \text{ (Eq. 13).}$$

Substituting Equation 12 into Equation 5 and expanding yields,

$$r^{harmonic} = \rho \frac{2(1+\epsilon_1)(1+\epsilon_2)}{2+\epsilon_1+\epsilon_2},$$

and hence the relative error of the equations estimate in Equation 13 is:

$$\frac{Em^{harmonic}_{estimated} - E_{true}}{E_{true}} = \frac{\epsilon_1+\epsilon_2+2\epsilon_1\epsilon_2}{2+\epsilon_1+\epsilon_2}, \text{ (Eq. 14).}$$

When the biases of 1 and 2 are opposed, these errors largely cancel, and when they are aligned, assuming small errors, $|\epsilon_1|, |\epsilon_2| \ll 1$, the error reduces to:

$$\frac{Em^{harmonic}_{estimated} - E_{true}}{E_{true}} \approx \frac{\epsilon_1+\epsilon_2}{2}, \text{ (Eq. 10).}$$

Hence using a harmonic mean of two inventories results in biases either canceling out, or the bias of the estimate lying between the biases of the two datasets. Because the magnitude and signs of the individual biases of CEDS and EDGAR are uncertain, the harmonic mean offers a more robust centralized estimate rather than choosing either inventory alone.

2.5. Uncertainty & Confidence

Uncertainty analysis was not performed for this initial development of air quality datasets; however, as the dataset matures, uncertainty of activity for sectors will be incorporated with the uncertainty of emissions factors and mitigation controls. As UQ was not performed and country-level mitigation and reduction technology is considered constant across facilities, the confidences of these estimates are considered *Very Low*.

3. Results

Climate TRACE emissions estimates for 2022 from Phase 7 and Phase 6 are in Table 1 as well as a comparison to CEDS and EDGAR global non-GHG emissions. NOx and CO had the largest changes between Phase 6 and Phase 7, becoming more aligned with CEDS and EDGAR. Comparatively, the order of magnitude of Climate TRACE non-GHG emissions estimates is fairly aligned with the comparable inventories for most gasses. EDGAR and CEDS substantially differ on global emissions estimates for SO_2, with Climate Trace being more aligned with the latter. Notably, PM_{10} has the largest discrepancy with the reference inventories, drastically underestimating global emissions. This is likely due to existing gaps in electricity-generation, road-transportation, shipping, and fires; however, PM_{10} is not planned to be released in Phase 7. Improvements on PM_{10} emissions and their release are planned for later releases.

Table 1. Global emissions estimate for each species per inventory for 2022 in MT.

Species	Climate TRACE Phase 7	Climate TRACE Phase 6	CEDS	EDGAR
BC	7.7	6.8	4.7	5.3
CO	422	563	450	410
NH_3	44	46	57	64
NMVOC	154	151	138	128
NO_X	110	91	110	106
OC	16	16	12	13
SO_2	85	84	84	69
$PM_{2.5}$	31	33	N/A	37
PM_{10}	26	N/A	N/A	58

The buildings sector is the largest anthropogenic source of $PM_{2.5}$, BC, OC, and CO; fossil fuel operations lead in the emissions of SO_2 and NMVOC; on-road transportation drives global NOx emissions; and agriculture dominates the emissions of NH_3 – as shown in Figure 1 in the Supplementary Materials section. This can inform how to effectively manage and mitigate global emissions. This includes GHG emissions reducing solutions that have a co-benefit of reducing pollution such as the electrification of buildings. A breakdown by country for each of the largest emitting sectors by country also reveals how economics and demographics can correlate with the amounts of emissions produced by a given country as shown in Figure 2 in the Supplementary Materials section. Naturally, countries with larger populations dominate pollution from buildings, whereas countries with large agricultural or fossil fuel industries have larger footprints in emissions from those sectors.

Figures 3 and 4, in the Supplementary Materials section, show a comparison across pollutants between Climate TRACE, EDGAR, and CEDS broken-up into individual countries and sectors. Across most sectors and gases, Climate TRACE national values align well with both EDGAR and CEDS, with correlation coefficients greater than 0.80 and normalized root-mean square errors less than 0.05 for nearly all sectors; however, Climate TRACE tends to under-estimate emissions from waste (brown-colored dots in Figures 3 and 4) across most gases compared to CEDS while simultaneously over-estimate compared to EDGAR. This speaks to the impact made by introducing a mixture of emissions ratios rather than solely relying on one inventory over the other. When compared to each other in Figure 5, EDGAR and CEDS disagree on waste emissions, whereas Climate TRACE sits between the two, acting as a consensus between these inventories. The introduction of more inventories may further improve these estimates.

4. Conclusions

Identifying sources of air pollution is the first step towards managing and mitigating it, and improvements made in Phase 7 to the Climate TRACE non-GHG model advances this goal. These include disaggregating pollution arising from process and combustion-related activities, utilizing a harmonic mixture of ratios leveraged from EDGAR and CEDS to reduce bias in the overall gap-filling model, extending coverage to $PM_{2.5}$, and refining upon individual sectors. The results of these changes are an overall improvement in Climate TRACE's global and country-level emissions.

Remaining gaps highlight the path forward. Incorporating sub-national inventories, aligning TRACE facilities with reported point-source data, further disaggregating mixed-source sectors, and assimilating top-down constraints from inversion modelling will all tighten uncertainties. As these improvements are introduced, Climate TRACE will provide an increasingly reliable inventory for decision-makers to mitigate air pollution, healthcare professionals to understand the impacts air pollution has on their patients, and scientists to analyze the impact of emissions on weather and the climate.

5. Acknowledgements

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6. Supplementary Materials

Table 2. Mapping of Climate TRACE sectors to CEDS sectors.

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Energy Industries and Fugitive Emissions	Electricity Generation	electricity-generation	1A1a_Electricity-autoproducer, 1A1a_Electricity-public
Energy Industries and Fugitive Emissions	Heat Plants	heat-plants	1A1a_Heat-production
Energy Industries and Fugitive Emissions	Other Energy Use	oil-and-gas-refining, other-energy-use	1A1bc_Other-transformation, 1A5_Other-unspecified
Energy Industries and Fugitive Emissions	Solid Fuels	coal-mining, solid-fuel-transformation	1B1_Fugitive-solid-fuels
Energy Industries and Fugitive Emissions	Oil and Gas Production and Transport	oil-and-gas-production, oil-and-gas-transport	1B2_Fugitive-petr, 1B2b_Fugitive-NG-prod
Energy Industries and Fugitive Emissions	Other Fossil Fuel Operations	other-fossil-fuel-operation s	1B2d_Fugitive-other-energy, 1B2b_Fugitive-NG-distr
Manufacturing and Industrial Processes	Cement	cement	2A1_Cement-production
Manufacturing and Industrial Processes	Metal Industry	iron-and-steel	1A2a_Ind-Comb-Iron-steel, 2C1_Iron-steel-alloy-prod
Manufacturing and Industrial Processes	Metal Industry	aluminum, other-metals	1A2b_Ind-Comb-Non-ferrous-metals, 2C3_Aluminum-production, 2C4_Non-Ferrous-other-metals
Manufacturing and Industrial Processes	Chemicals	chemicals, petrochemical-steam-crac king, other-chemicals	1A2c_Ind-Comb-Chemicals, 2B_Chemical-industry, 2B2_Chemicals-Nitric-acid, 2B3_Chemicals-Adipic-acid
Manufacturing and Industrial Processes	Pulp and Paper	pulp-and-paper	1A2d_Ind-Comb-Pulp-paper
Manufacturing and Industrial Processes	Mining and Quarrying	sand-quarrying, rock-quarrying, bauxite-mining, iron-mining, copper-mining, other-mining-quarrying	1A2g_Ind-Comb-mining-quarying
Manufacturing and Industrial Processes	Food Beverage and Tobacco	food-beverage-tobacco	1A2e_Ind-Comb-Food-tobacco
Manufacturing and Industrial Processes	Textiles Leather and Apparel	textiles-leather-apparel	1A2g_Ind-Comb-textile-leather
Manufacturing and Industrial Processes	Wood and Wood Products	wood-and-wood-products	1A2g_Ind-Comb-wood-products
Manufacturing and Industrial Processes	Lime	lime	2A2_Lime-production
Manufacturing and Industrial Processes	Glass	glass	2Ax_Other-minerals
Manufacturing and Industrial Processes	Other Manufacturing	other-manufacturing, fluorinated-gases	1A2f_Ind-Comb-Non-metalic-minerals, 1A2g_Ind-Comb-Construction, 1A2g_Ind-Comb-machinery, 1A2g_Ind-Comb-other, 1A2g_Ind-Comb-transpequip, 2D_Chemical-products-manufacture-pro cessing, 2D_Degreasing-Cleaning, 2D_Other-product-use, 2D_Paint-application, 2H_Pulp-and-paper-food-beverage-wood
Transport	Domestic Aviation	domestic-aviation	1A3aii_Domestic-aviation

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	CEDS Sectors
Transport	International Aviation	international-aviation	1A3ai_International-aviation
Transport	Domestic Shipping	domestic-shipping	1A3dii_Domestic-navigation
Transport	International Shipping	international-shipping	1A3di_International-shipping, 1A3di_Oil_Tanker_Loading
Transport	Road Transportation	road-transportation	1A3b_Road
Transport	Railways	railways	1A3c_Rail
Transport	Other Transport	other-transport	1A3eii_Other-transp
Buildings	Residential Onsite Fuel Usage	residential-onsite-fuel-usage	1A4b_Residential
Buildings	Non-Residential Onsite Fuel Usage	non-residential-onsite-fuel-usage	1A4a_Commercial-institutional
Buildings	Other Onsite Fuel Usage	other-onsite-fuel-usage	1A4c_Agriculture-forestry-fishing
Agriculture	Enteric Fermentation	enteric-fermentation-cattle-operation, enteric-fermentation-cattle-pasture, enteric-fermentation-other	3E_Enteric-fermentation
Agriculture	Manure Management	manure-management-cattle-operation, manure-management-other, manure-left-on-pasture-cattle	3B_Manure-management
Agriculture	Rice Cultivation	rice-cultivation	3D_Rice-Cultivation
Agriculture	Direct Nitrogen Emissions from Agricultural Soils	synthetic-fertilizer-application, manure-applied-to-soils, crop-residues, soil-organic-carbon	3D_Soil-emissions
Agriculture	Other Agriculture	other-agricultural-soil-emissions	3I_Agriculture-other, 7BC_Indirect-N2O-non-agricultural-N
Waste	Solid Waste Disposal	solid-waste-disposal	5A_Solid-waste-disposal
Waste	Other Waste	biological-treatment-of-solid-waste-and-biogenic	5E_Other-waste-handling
Waste	Incineration and Open Burning of Waste	incineration-and-open-burning-of-waste	5C_Waste-combustion
Waste	Wastewater Treatment and Discharge	industrial-wastewater-treatment-and-discharge, domestic-wastewater-treatment-and-discharge	5D_Wastewater-handling
Forestry and Land Use Change	Biomass Burning	forest-land-fires, shrubgrass-fires, wetland-fires, cropland-fires,	
Forestry and Land Use Change	Emissions and Removals Excluding Biomass Burning	forest-land-clearing, forest-land-degradation, removals, water-reservoirs	

Table 3. Mapping of Climate TRACE sectors to EDGAR sectors.

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	EDGAR Sectors
Energy Industries and Fugitive Emissions	Electricity Generation and Other Energy Use	electricity-generation, heat-plants, other-energy-use	1.A.1.a Main Activity Electricity and Heat Production
Energy Industries and Fugitive Emissions	Fossil Fuel Operations	coal-mining, other-solid-fuels, oil-and-gas-production, oil-and-gas-transport, oil-and-gas-refining, other-fossil-fuel-operations	1.B.1 Solid Fuels, 1.B.2 Oil and Natural Gas, 1.A.1.bc Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries
Transport	Domestic Aviation	domestic-aviation	1.A.3.a Civil Aviation
Transport	Domestic Shipping	domestic-shipping	1.A.3.d Water-borne Navigation
Transport	International Aviation and Shipping	international-aviation, international-shipping	
Transport	Road Transportation	road-transportation	1.A.3.b_noRES Road Transportation no resuspension
Transport	Railways	railways	1.A.3.c Railways
Transport	Other Transport	other-transport	1.A.3.e Other Transportation
Buildings	Residential and Commercial Onsite Fuel Usage	residential-onsite-fuel-usage, non-residential-onsite-fuel-usage	1.A.4 Residential and other sectors
Buildings	Other Onsite Fuel Usage	other-onsite-fuel-usage	1.A.5 Non-Specified
Manufacturing and Industrial Processes	Cement	cement	2.A.1 Cement production
Manufacturing and Industrial Processes	Chemicals	petrochemical-steam-cracking, chemicals, other-chemicals	2.B Chemical Industry
Manufacturing and Industrial Processes	Metal Industry	steel, aluminum, other-metals	2.C Metal Industry
Manufacturing and Industrial Processes	Fluorinated Gases	fluorinated-gases	2.F Product Uses as Substitutes for Ozone Depleting Substances
Manufacturing and Industrial Processes	Lime	lime	2.A.2 Lime production
Manufacturing and Industrial Processes	Glass	glass	2.A.3 Glass Production
Manufacturing and Industrial Processes	Other Manufacturing and Industrial Processes	pulp-and-paper, food-beverage-tobacco, wood-and-wood-products, textiles-leather-apparel, other-manufacturing, sand-quarrying, rock-quarrying, bauxite-mining, iron-mining, copper-mining, other-mining-quarrying	1.A.2 Manufacturing Industries and Construction, 2.G Other Product Manufacture and Use, 2.D Non-Energy Products from Fuels and Solvent Use, 2.E Electronics Industry, 2.A.4 Other Process Uses of Carbonates
Agriculture	Enteric Fermentation	enteric-fermentation-cattle-operation, enteric-fermentation-cattle-pasture, enteric-fermentation-other	3.A.1 Enteric Fermentation
Agriculture	Manure Management	manure-management-cattle-operation,	3.A.2 Manure Management, 3.C.6 Indirect N2O Emissions from manure management

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	EDGAR Sectors
		manure-management-other, manure-left-on-pasture-cattle	
Agriculture	Rice Cultivation	rice-cultivation	3.C.7 Rice cultivations
Agriculture	Direct Nitrogen Emissions from Agricultural Soils	synthetic-fertilizer-application, manure-applied-to-soils, crop-residues, manure-left-on-pasture-cattle	3.C.4 Direct N2O Emissions from managed soils, 3.C.5 Indirect N2O Emissions from managed soils
Agriculture	Other Agriculture	other-agricultural-soil-emissions	3.C.2 Liming, 3.C.3 Urea application, 5.A Indirect N2O emissions from the atmospheric deposition of nitrogen in NOx and NH3
Fires	Biomass Burning	cropland-fires, forest-land-fires, shrubgrass-fires, wetland-fires	3.C.1 Emissions from biomass burning
Waste	Solid Waste Disposal	solid-waste-disposal	4.A Solid Waste Disposal
Waste	Biological Treatment of Solid Waste	biological-treatment-of-solid-waste-and-biogenic	4.B Biological Treatment of Solid Waste
Waste	Incineration and Open Burning of Waste	incineration-and-open-burning-of-waste	4.C Incineration and Open Burning of Waste
Waste	Wastewater Treatment and Discharge	industrial-wastewater-treatment-and-discharge, domestic-wastewater-treatment-and-discharge	4.D Wastewater Treatment and Discharge
Forestry and Land Use Change	Forestry and Land Use Change	forest-land-clearing, forest-land-degradation, removals, water-reservoirs	
Agriculture	Enteric Fermentation	enteric-fermentation-cattle-operation, enteric-fermentation-cattle-pasture, enteric-fermentation-other	3E_Enteric-fermentation
Agriculture	Manure Management	manure-management-cattle-operation, manure-management-other, manure-left-on-pasture-cattle	3B_Manure-management
Agriculture	Rice Cultivation	rice-cultivation	3D_Rice-Cultivation
Agriculture	Direct Nitrogen Emissions from Agricultural Soils	synthetic-fertilizer-application, manure-applied-to-soils, crop-residues, soil-organic-carbon	3D_Soil-emissions
Agriculture	Other Agriculture	other-agricultural-soil-emissions	3I_Agriculture-other, 7BC_Indirect-N2O-non-agricultural-N
Waste	Solid Waste Disposal	solid-waste-disposal	5A_Solid-waste-disposal
Waste	Other Waste	biological-treatment-of-solid-waste-and-biogenic	5E_Other-waste-handling

Comparison Sector	Comparison Subsector	Climate TRACE Sectors	EDGAR Sectors
Waste	Incineration and Open Burning of Waste	incineration-and-open-burning-of-waste	5C_Waste-combustion
Waste	Wastewater Treatment and Discharge	industrial-wastewater-treatment-and-discharge, domestic-wastewater-treatment-and-discharge	5D_Wastewater-handling

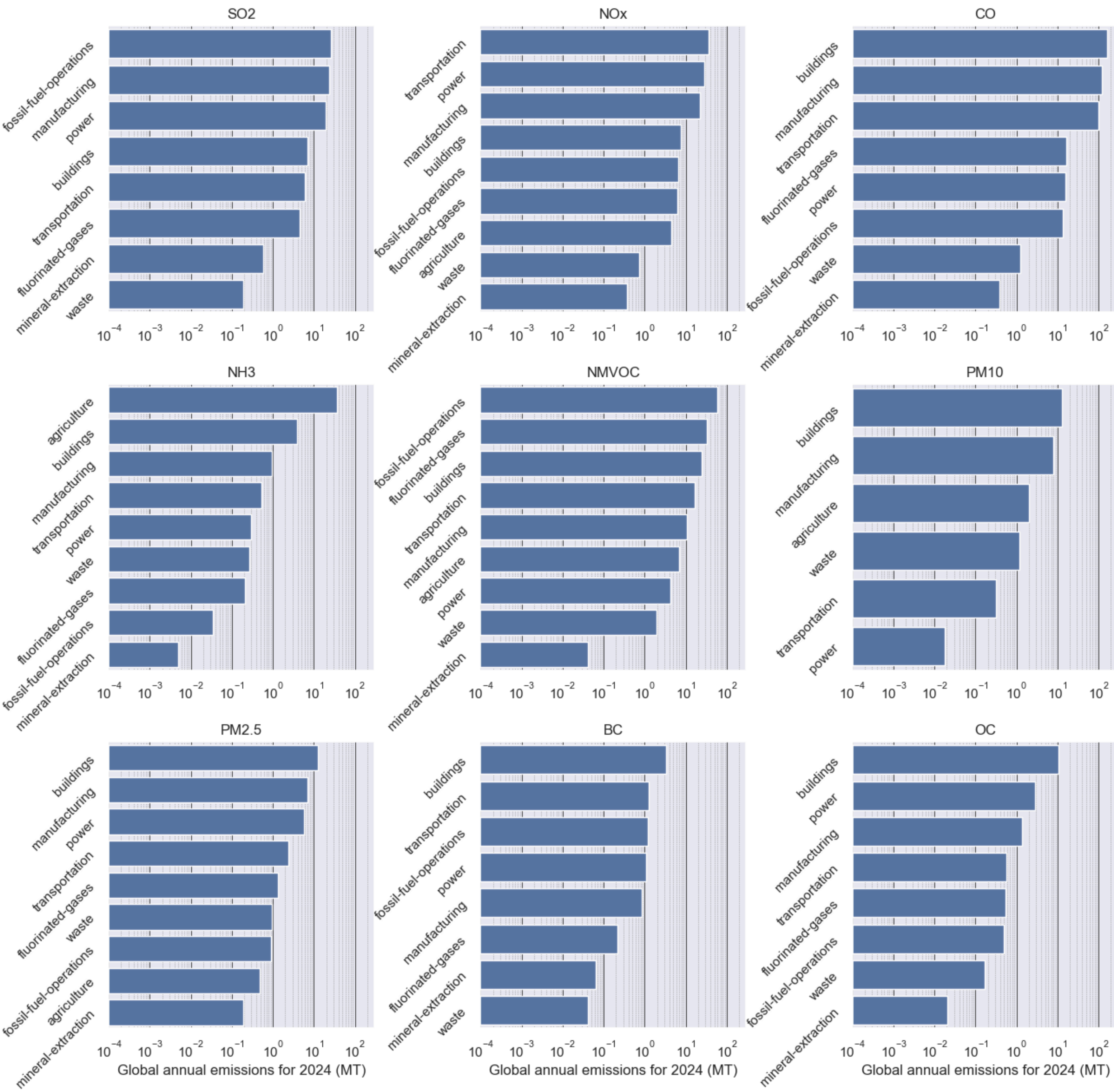

Figure 1: Global emissions sector breakdown across all studied pollutants – missing sectors indicate that those do not produce any emissions for the corresponding gas.

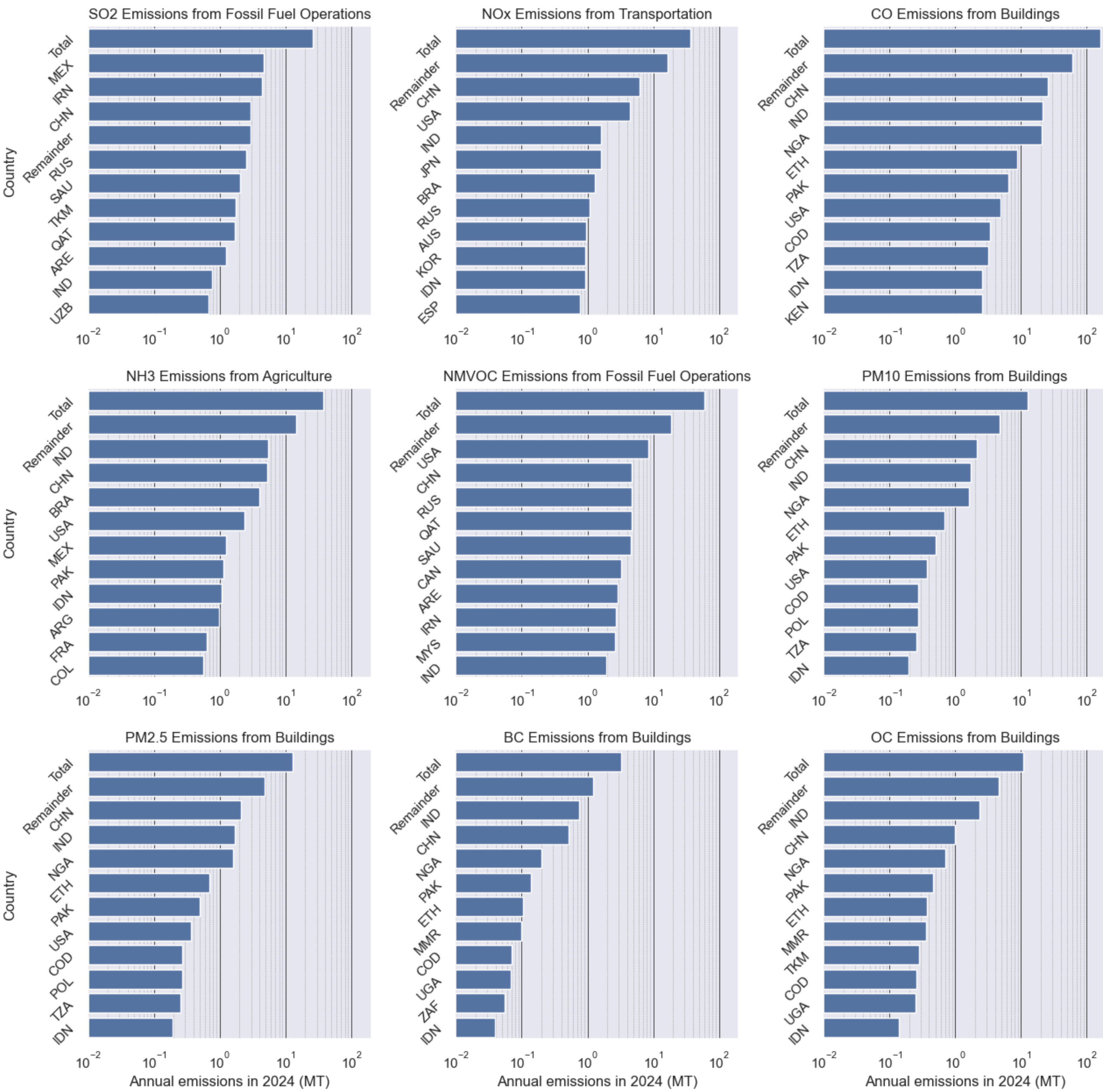

Figure 2: Top ten largest emitters, total emissions, and remaining global emissions for the largest sector for each gas.

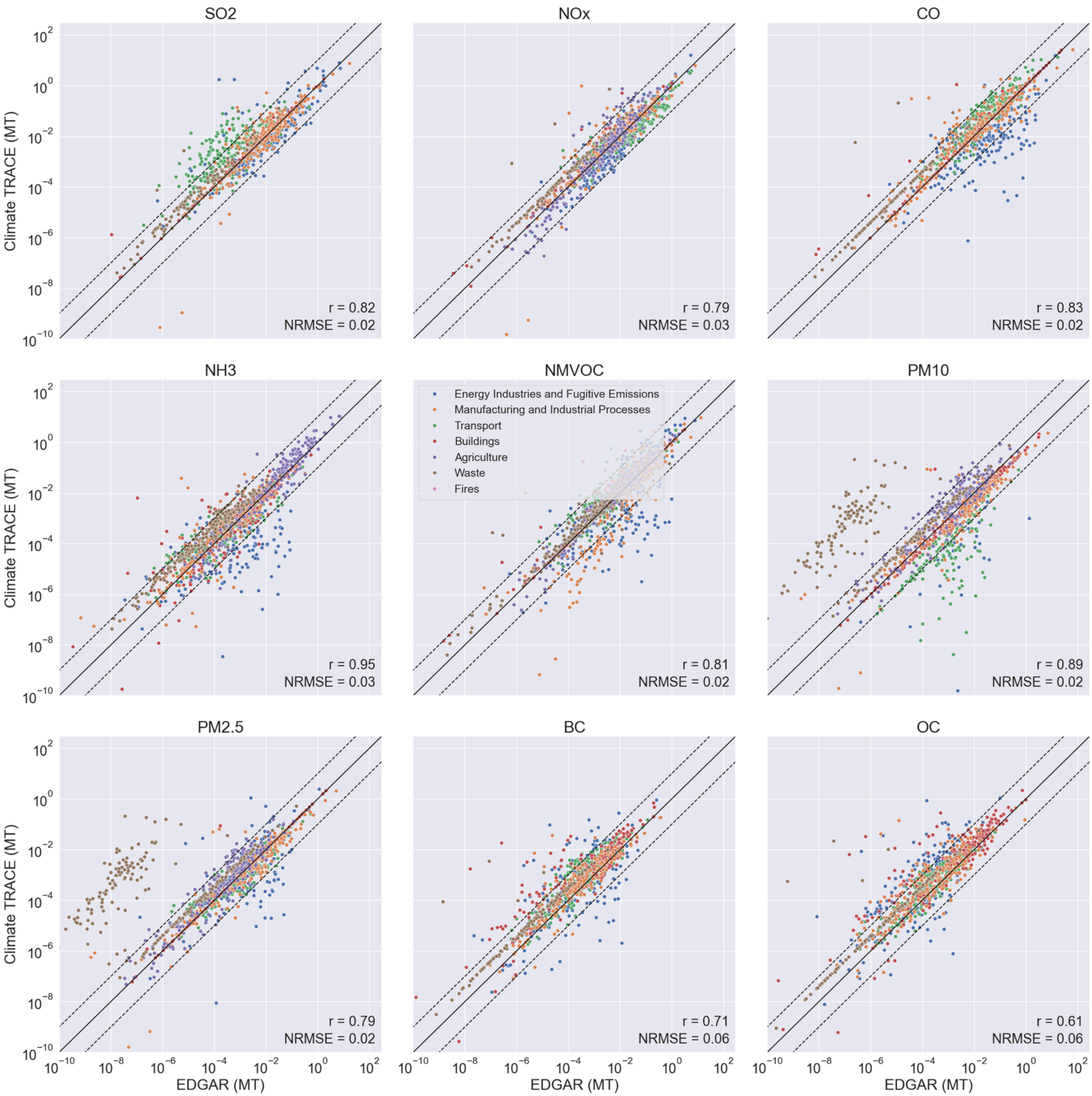

Figure 3: A comparison between Climate TRACE and EDGAR across sectors and gases. The black solid-line is the unit line, with the black dashed-lines displaying one order of magnitude above and below the unit line. All emissions are measured in MT with each dot representing a single country. Normalized root mean squared error (NRMSE) was calculated with the range of the EDGAR emissions as reference.

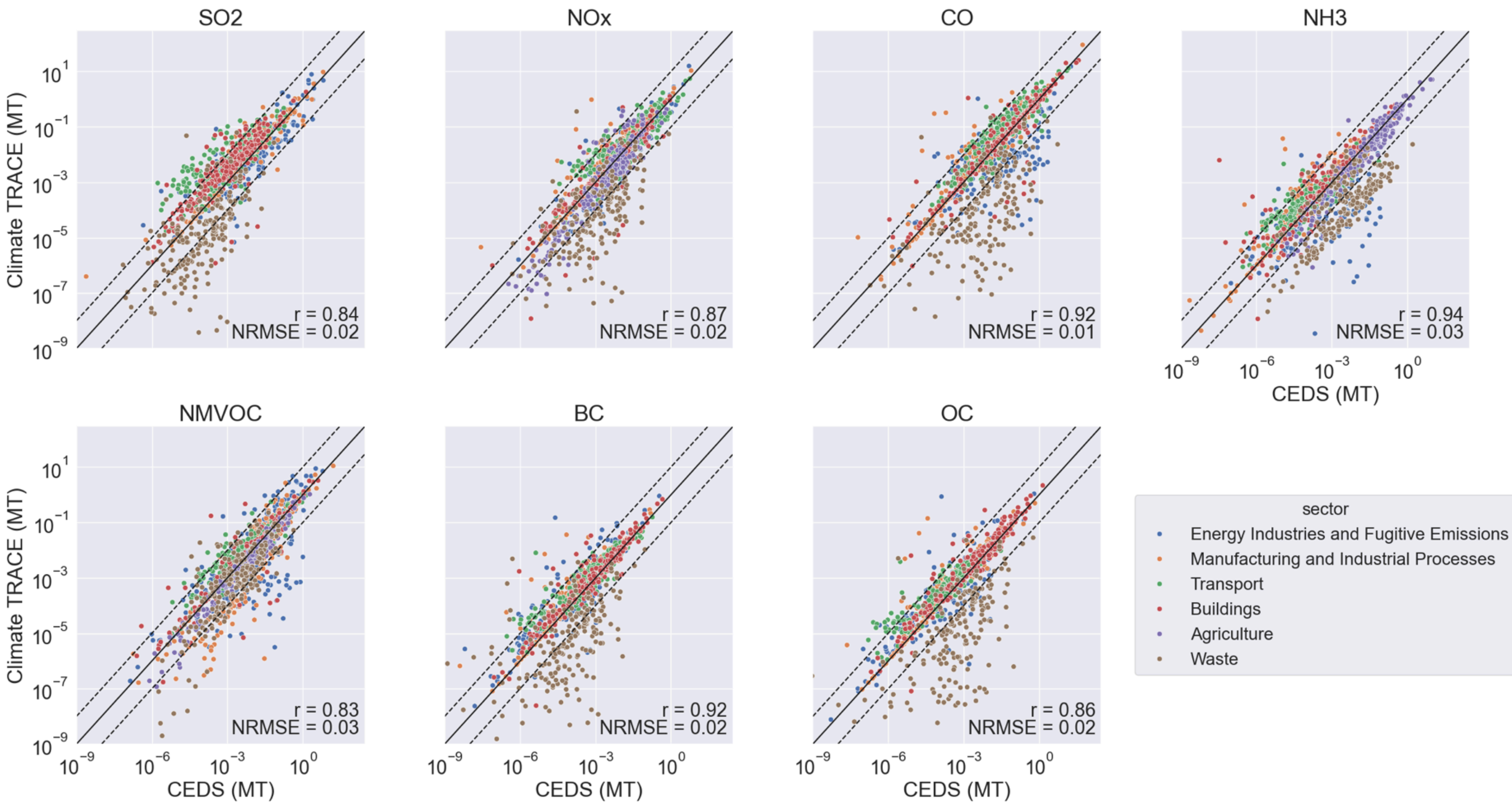

Figure 4: A comparison between CEDS and Climate TRACE across sectors and gases. The black solid-line is the unit line, with the black dashed-lines displaying one order of magnitude above and below the unit line. All emissions are measured in megatonnes (MT) with each dot representing a single country. NRMSE was calculated with the range of the CEDS emissions as reference.

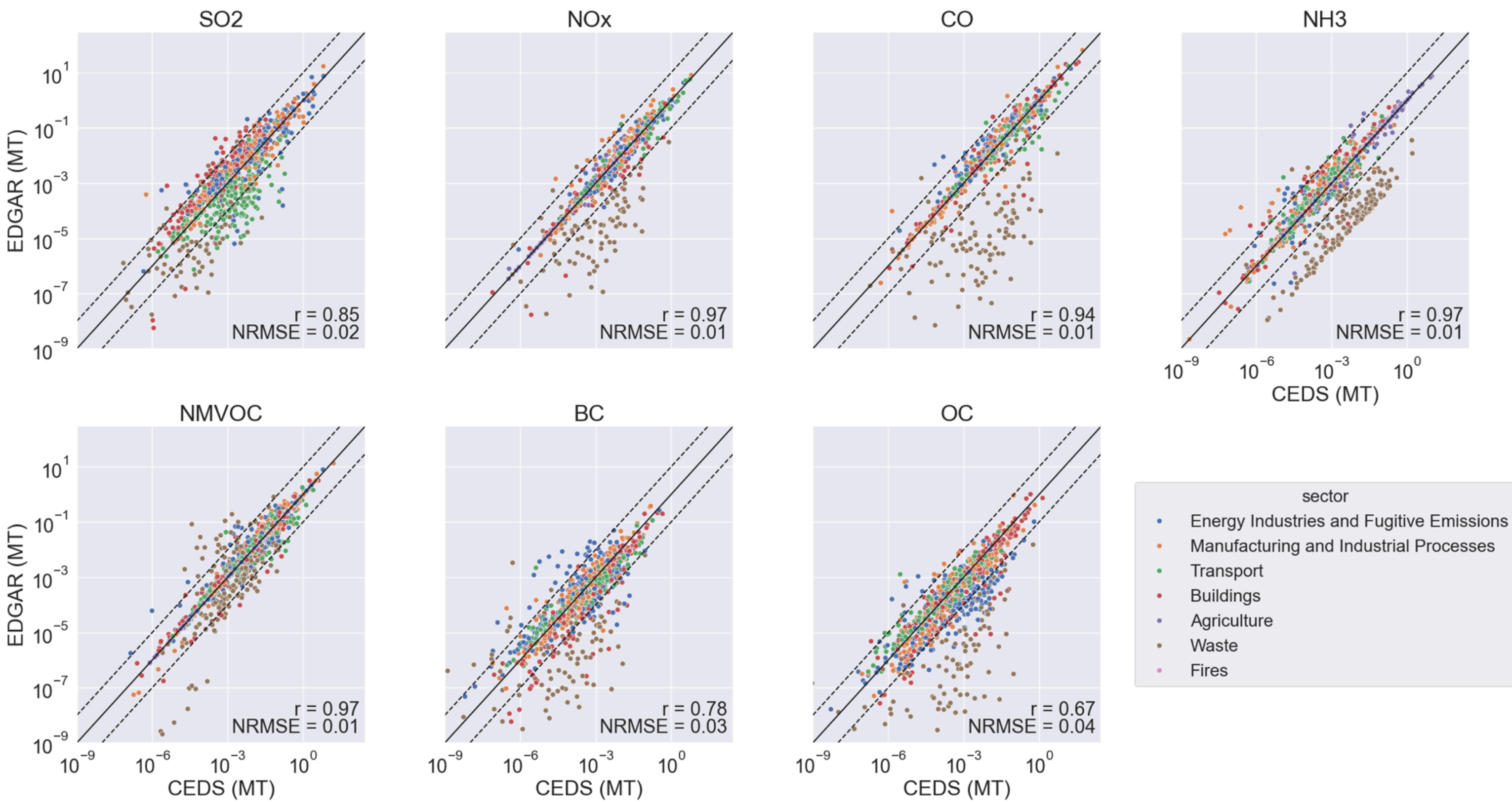

Figure 5: A comparison between EDGAR and CEDS across sectors and gases. The black solid-line is the unit line, with the black dashed-lines displaying one order of magnitude above and below the unit line. All emissions are measured in megatonnes (MT) with each dot representing a single country. NRMSE was calculated with the range of the CEDS emissions as reference.

Table 4. Country proxy used for emissions estimates. As CEDS does not provide emissions estimates for 31 regions, they are mapped to respective proxy countries based on geography, cultural ties, and governmental relationships. Countries mapped to *zero* imply that no compatible mapping was needed.

Country	Proxy Country	Country	Proxy Country	Country	Proxy Country	Country	Proxy Country
AIA	GRB	CCK	LKA	MCO	ITA	SHN	GBR
ALA	FIN	CXR	LKA	MNP	ASM	SJM	NOR
AND	FRA	GGY	GBR	MYT	LKA	SMR	ITA
ATA	zero	HMD	zero	NFK	AUS	TUV	ASM
ATF	SXM	IMN	GBR	NRU	ASM	UMI	ASM
BES	SXM	IOT	GBR	PCN	AUS	VAT	ITA
BLM	FRA	JEY	GBR	PSE	LBN	ZNC	TUR
BVT	zero	MAF	FRA	SGS	GBR	UNK	zero

Data citation format: Collins, G., Robinette, M., Sridhar, L., Reilly, E., Hughes, M. (2025). *Non-Greenhouse Gas Emissions Estimates Across Sectors.* The Johns Hopkins University Applied Physics Laboratory (JHU/APL), USA, WattTime, USA, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

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.

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.

7. References

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