Comparison of observation- and inventory- based methane emissions for eight large global emitters

Ana Maria Roxana Petrescu[1], Glen P. Peters[2], Richard Engelen[3], Sander Houweling[1], Dominik Brunner[4], Aki Tsuruta[5], Bradley Matthews[6], Prabir K. Patra[7,8,9], Dmitry Belikov[9], Rona L. Thompson[10], Lena Höglund-Isaksson[11], Wenxin Zhang[12], Arjo J. Segers[13], Giuseppe Etiope[14,15], Giancarlo Ciotoli[16,14], Philippe Peylin[17], Frédéric Chevallier[17], Tuula Aalto[5], Robbie M. Andrew[2], David Bastviken[18], Antoine Berchet[17], Grégoire Broquet[17], Giulia Conchedda[19], Johannes Gütschow[20], Jean-Matthieu Haussaire[4], Ronny Lauerwald[21], Tiina Markkanen[5], Jacob C. A. van Peet[1], Isabelle Pison[17], Pierre Regnier[22], Espen Solum[10], Marko Scholze[12], Maria Tenkanen[5], Francesco N. Tubiello[19], Guido R. van der Werf[23], John R. Worden[24]

[1]Department of Earth Sciences, Vrije Universiteit Amsterdam, 1081HV, Amsterdam, the Netherlands

[2]CICERO Center for International Climate Research, Oslo, Norway

[3]European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, RG2 9AX, UK

[4]Empa, Swiss Federal Laboratories for Materials Science and Technology, 8600 Dübendorf, Switzerland

[5]Finnish Meteorological Institute, P. O. Box 503, FI-00101 Helsinki, Finland

[6]Umweltbundesamt GmbH, Climate change mitigation & emission inventories, 1090, Vienna, Austria

[7]Research Institute for Humanity and Nature, Kyoto 6038047, Japan

[8]Research Institute for Global Change, JAMSTEC, Yokohama 2360001, Japan

[9]Chiba University, 1-33 Yayoicho, Inage Ward, Chiba, 263-8522, Japan

[10]NILU - Norsk Institutt for Luftforskning, Kjeller, Norway

[11]International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria

[12]Department of Physical Geography and Ecosystem Science, Lund University, SE-223 62 Lund, Sweden

[13]Department of Climate, Air and Sustainability, TNO, Princetonlaan 6, 3584 CB Utrecht, the Netherlands

[14]Istituto Nazionale di Geofisica e Vulcanologia, Sezione Roma 2, via V. Murata 605, Roma, Italy

[15]Faculty of Environmental Science and Engineering, Babes-Bolyai University, Cluj-Napoca, Romania

[16]Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria, Via Salaria km 29300, 00015 Monterotondo, Rome, Italy

[17]Laboratoire des Sciences du Climat et de l'Environnement, 91190 Gif-sur-Yvette, France

[18]Department of Thematic Studies – Environmental Change, Linköping University, Sweden

[19]Food and Agriculture Organization of the United Nations, Statistics Division. 00153 Rome, Italy

[20]Climate Resource, Northcote, Australia

[21]Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Palaiseau, France

[22]Biogeochemistry and Modeling of the Earth System, Université Libre de Bruxelles, 1050 Bruxelles, Belgium

[23]Meteorology and Air Quality Groep, Wageningen University and Research, Wageningen, the Netherlands

[24]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Correspondence to: A.M. Roxana Petrescu (a.m.r.petrescu@vu.nl)

Abstract

Monitoring the spatial distribution and trends in surface greenhouse gas (GHG) fluxes, as well as flux attribution to natural and anthropogenic processes, is essential to track progress under the Paris Agreement and to inform its Global Stocktake. This study updates earlier syntheses (Petrescu et al., 2020, 2021, 2023a) and provides a consolidated synthesis of CH_4 emissions using bottom-up (BU) and top-down (TD) approaches for the European Union (EU) and is expanded to include seven additional countries with large anthropogenic and/or natural emissions (USA, Brazil, China, India, Indonesia, Russia, and the Democratic Republic of Congo (DR Congo)). Our aim is to demonstrate the use of different emission estimates to help improve national GHG emission inventories for a diverse geographical range of stakeholders.

We use updated National GHG Inventories (NGHGIs) reported by Annex I Parties under the United Nations Framework Convention on Climate Change (UNFCCC) in 2023 and the latest available Biennial Update Reports (BURs) reported by non-Annex I Parties. Comparing NGHGIs with other approaches highlights that different system boundaries are a key source of divergence. A key system boundary difference is whether both anthropogenic and natural fluxes are included and, if they are, how fluxes belonging to these two sources are partitioned.

Over the studied period, the total CH_4 emission estimates in the EU, USA, and Russia show a steady decreasing trend since 1990, while for the non-Annex I emitters analyzed in this study, Brazil, China, India, Indonesia, and DR Congo, CH_4 emissions have generally increased. Quantitatively, in the **EU** the mean of 2015-2020 anthropogenic UNFCCC NGHGIs (15 ± 1.8 Tg CH_4 yr^{-1}) and the mean of the BU CH_4 emissions (17.8 (16-19) Tg CH_4 yr^{-1}) generally agree on the magnitude, while inversions show higher emission estimates (medians of 21 (19-22) Tg CH_4 yr^{-1} and 24 (22-25) Tg CH_4 yr^{-1} for the three regional and six global inversions, respectively), as they include natural emissions, which for the EU were quantified at 6.6 Tg CH_4 yr^{-1} (Petrescu et al., 2023a). Similarly, for the other Annex I Parties in this study (**USA and Russia**), the gap between the BU anthropogenic and total TD emissions is partly explained by the natural emissions.

For the **non-Annex I Parties**, anthropogenic CH_4 estimates from UNFCCC BURs show large differences with the other global inventory-based estimates and even more with atmospheric-based ones. This poses an important potential challenge to monitoring the progress of the global CH_4 pledge and the Global Stocktake. Our analysis provides a useful baseline to prepare for the influx of inventories from non-Annex I Parties as regular reporting starts under the Enhanced Transparency Framework of the Paris Agreement.

By systematically comparing the BU with TD methods, this study provides recommendations for more robust comparisons of available data sources and hopes to steadily engage more Parties in using observational methods to complement their UNFCCC inventories, as well as considering their natural emissions. With anticipated improvements in atmospheric modeling and observations, as well as modeling of natural fluxes, future development needs to resolve knowledge gaps in both BU and TD approaches and to better quantify

remaining uncertainty. TD methods may emerge as a powerful tool to help improve NGHGIs of CH_4 emissions, but further confidence is needed in the comparability and robustness of the estimates.

The referenced datasets related to figures are available at https://doi.org/10.5281/zenodo.12582667 (Petrescu et al., 2023b).

1. Introduction

In 2021, the NOAA Global Monitoring Laboratory (GML) reported the largest annual increase in atmospheric CH_4 mixing ratios since records began in 1983, at 17 parts per billion (ppb) (NOAA (https://gml.noaa.gov/ccgg/trends_ch4/). In 2022, atmospheric CH_4 concentrations averaged 1912 ppb yr^{-1}, 162 % higher than pre-industrial levels. A similar, abnormally large growth rate of 14.8 ppb yr^{-1} was detected from total column mixing ratio measurements (XCH_4) by the Greenhouse Gases Observing Satellite (GOSAT) (Peng et al., 2022). .

CH_4 in the atmosphere has many different sources, of both natural and anthropogenic origin. The natural sources of CH_4 are dominated by wetlands, while anthropogenic emissions principally come from agricultural activities (livestock and rice farming), waste management (landfills and water treatment plants) and the production, transportation, and use of fossil fuels. Most of the agricultural sources are distributed sources, while the energy-related industrial sources of CH_4 are a mix of large point sources, of which some are detectable by satellite (Jacob et al., 2022) and smaller point and distributed sources of fugitive emissions (e.g., leaks in pipelines and compression stations), which are more challenging to identify (Rutherford et al., 2021; Omara et al., 2022).

While anthropogenic CH_4 emissions from fossil fuels, agriculture, and waste can be reduced by mitigation actions, increased natural emissions lead to different challenges. It has been suggested that the drivers of the recent growth are most likely driven primarily by biogenic emissions (Basu et al., 2022; Lan, et al., 2021a; Lanet al., 2021b; Lan et al., 2022; Nisbet et al., 2016, 2019), with smaller contributions from increased fossil fuel emissions and a reduced atmospheric sink (Nisbet et al., 2023). Fluctuations in natural sources - dominated by wetlands and open water bodies - were the main reasons for some of the atmospheric CH_4 anomalies observed during the last decades (Rocher-Ros et al., 2023; Zhang et al., 2023; Nisbet et al., 2023; Lunt et al., 2019). Nisbet et al., 2023 review recent studies, including those which quantified the observed methane growth in the last years. Using a global inverse analysis of GOSAT satellite observations, increases in the range of 22-32 Tg CH_4 yr^{-1} were detected between 2019and 2020 and were attributed to biogenic sources, half of which took place in East Africa (~ 15 Tg yr^{-1}), and some were observed in Canada and Alaska (4.8 Tg yr^{-1})(Qu et al., 2022 and Basu et al., 2022).

Chandra et al., 2021 identified a few main sectors that triggered increases and decreases in the anthropogenic CH_4 emissions of different countries. The first is energy, with its fugitive emissions from the oil and gas industry whose decline in emissions helped stabilize CH_4 concentration in the 1990s, before they contributed to the renewed CH_4 growth since the late 2000s (increased emissions). The other major sectors that drove changes in the CH_4 growth rate were agriculture (increase in emissions from enteric fermentation and manure management) and waste. The increase in emissions from enteric fermentation and manure management was caused primarily by increased animal numbers, and in addition by the greater intensity of ruminant farming as estimated by the FAO and the emission inventories (e.g. EDGAR) which might take into account productivity increases (Crippa et al., 2020; Wolf et al., 2017; FAOSTAT, 2018) while inventory emissions from waste can account for up to 43 % of the linear increase in emissions for the rest of the world.

The contribution of CH_4 to global warming has been estimated to be about 0.5ºC relative to the period 1850–1900 (IPCC, 2021) (Stavert et al., 2022). Methane has a relatively short perturbation lifetime (averaging 12.4 years, Balcombe et al., 2018) and a high global warming potential (86 and 34 for 20- and 100-years times horizons respectively, compared to that of CO_2 emissions, IPCC, 2021, Table 7.15). Given the short lifetime, a decline in CH_4 emissions will rapidly reduce the global warming contribution from CH_4 and help mitigate the impact of climate change at decadal time scale (Cain et al., 2021). However, efforts to reduce CH_4 emissions require a thorough understanding of the dominant CH_4 sources and sinks and their temporal and regional distribution and trends (Stavert et al., 2022).

The Paris Agreement, a milestone of the UNFCCC to combat climate change and adapt to its effects, entered into force on November 4, 2016. It asks each signatory to define and communicate its planned climate actions, known as Nationally Determined Contributions (NDCs), and to report their progress towards their targets. Next to commitments adopted by countries at COP26, the Global Methane Pledge (GMP) was launched. The goal of the GMP is to cut anthropogenic CH_4 emissions by at least 30 % by 2030 with respect to 2020 levels and is seen as the fastest way to reduce near-term warming and is necessary to keep a 1.5°C temperature limit within reach. Achieving this goal will drive significant gains, through specific energy and agriculture defined pathways including innovative actions, national targeted policies, and green climate funds to help smallholder farmers (https://www.state.gov/global-methane-pledge-from-moment-to-momentum/). About 150 countries joined this pledge and about fifty have already developed national CH4 action plans or are doing so. As agriculture and waste are the main anthropogenic sources for CH_4 emissions, a GMP Food and agriculture pathway and a GMP waste pathway were launched at COP27, foreseeing actions that increase agricultural productivity, while reducing emissions from dairy, food loss and waste by supporting small farmers and innovation (https://www.state.gov/global-methane-pledge-from-moment-to-momentum/).

Starting in 2024, non-Annex I Parties to the UNFCCC must - given they have sufficient capacities - report formal inventories under the Paris Agreement's Enhanced Transparency Framework following the same guidelines and rules as the Annex I countries (Perugini et al., 2021). Furthermore, they will undergo more stringent reviews than those that previously looked at the Biennial Update Reports (BURs) and NDCs. This will also allow strengthening the robustness of such comparison exercises when using independent atmospheric observations in estimating trends and patterns for regional and national CH_4 emissions (IPCC, 2006). The influx of new inventories will place additional demands on independent emission estimates to help improve and inform National Greenhouse Gas Inventories (NGHGIs), particularly in countries with low capacity.

With increased focus on CH_4 in climate policy, there is a demand to ensure that planned emission reductions are realized. Further, as non-Annex I countries begin regular reporting of emission estimates under the Enhanced Transparency Framework, there is a need to help countries improve their GHG emission estimates. This has created an active field of research comparing NGHGI and independent estimates. Our analysis builds on the three-year EU funded project $CoCO_2$, which had as main objective the building of prototype systems for a European Monitoring and Verification Support capacity for anthropogenic CO_2 (and CH_4) emissions (CO_2MVS). In this context, one of the results of the CoCO$_2$ project was the production of a Blueprint for a decision support system to be used in an eventual CO_2MVS, aiming at informing and attracting attention of diverse climate stakeholders on the use of the results needed beyond research. Therefore, the objectives of this study reflect those of the Blueprint and focus on user engagement. It builds on dialogues with a broad community of users (e.g. scientists, inventory agencies, policy makers), considering their opinions and needs when it comes to comparisons between independent approaches. Furthermore, this study expands beyond the EU to include seven countries that have large anthropogenic and/or natural CH_4 emissions (USA, Brazil, China, India, Indonesia, Russia and the Democratic Rep. of Congo). It examines both Annex I (EU, USA and Russia) and non-Annex I estimates from observation-based BU process-based models and inversions-based TD approaches (using satellite observations) by identifying and explaining differences with official inventory reports submitted by parties to the UNFCCC. The seven countries were chosen based on location and the importance / magnitude of their anthropogenic and natural emissions. By using multiple methodologies, uncertainties can be estimated by looking at the range in both emissions and trends.

2. Methods and data

In this work we focus on comparing BU and TD emission estimates. The 'reconciliation process' described in this work is the action of making one dataset comparable with another to assess their consistency. In this respect, we attempt to obtain consistent results from both BU and TD estimates, through harmonization of the results, concepts and definitions. After the reconciliation process, the estimates do not necessarily agree, representing uncertainties in the different methods and datasets. We now describe the key data and methods used in our analysis.

2.1. Verification practices in official UNFCCC NGHGIs

Quality assurance/quality control (QA/QC) is a key component of NGHGIs development. Verification is an additional step and refers specifically to methods that are external to the inventory and apply independent data. There are two main methods of verification: 1) independent inventory-based estimates, 2) observation-based emission estimates.

A challenge with comparisons against *independent inventory-based estimates* is that none of them is truly independent as they may rely on, for example, the same activity data reported by a country (Andrew 2020). Experience has shown that performing detailed comparisons (Petrescu et al., 2021, 2023a, Lauerwald et al., 2024) can help clarify differences in system boundaries or even identify errors (Andrew 2020). Improving independent emission inventories also has value, as these are often used in global studies where common methods across all countries are desired.

Observation-based estimates use observations of atmospheric concentrations and prior fluxes that are then coupled to a transport model. These methods are more complex and computationally expensive and can make use of both direct observations and emission inventories.

The 2019 refinement of the 2006 IPCC guidelines highlighted notable advances in the application of inverse models of atmospheric transport for estimating emissions at the national scale. Building on this progress, they extend the guidance on the use of atmospheric measurements for verification (IPCC, 2019). There are several countries that currently use atmospheric measurements for verification of parts of their inventories. Australia (Luhar et al 2020, AUS NIR, 2023) and New Zealand (Geddes et al., 2021) have estimated regional CH_4 emissions to help better understand the methods and their potential. Germany performs various cross-validation checks with available data (German NIR, 2023), some of which are based on observations. The UK and Switzerland (Annex 6 CHE NIR, 2023) have developed more comprehensive methods based on inversion modeling, covering several GHGs in addition to CH_4. Building on modeling experience, the country reporting confirms that most potential lies in using observations to verify fluorinated gases (Annex 6 UK NIR, 2023), but the large uncertainty in CH_4 emissions gives the potential for verification if a sufficient observation network is used in inversion modeling (Bergamaschi et al., 2018, Thompson et al., 2014).

While inversions of CH_4 fluxes are associated with significant uncertainty, so are NGHGI estimates of anthropogenic CH_4 emissions. Furthermore, inversions can provide information on subannual and subnational variations in time and space that may indicate differences in source sector emission estimates. In geographic areas with sufficiently dense ground-based observation networks, the inversions will have more value.

2.2. Anthropogenic CH_4 emissions from the NGHGIs

Annex I countries report their annual GHG emissions to the UNFCCC in the so-called Common Reporting Format (CRFs) data tables and National Inventory Reports (NIRs). Here, anthropogenic CH_4 emissions from the five UNFCCC sectors, incl. Land Use, Land Use Change and Forestry (LULUCF) are grouped together. As part of the LULUCF sector, we also have the CH_4 emissions from wetlands, which according to the IPCC guidelines are defined as managed "where the water table is artificially changed (i.e. lowered or raised) or those created through human activity (e.g. damming a river) and that do not fall into Forest Land, Cropland, or Grassland categories (IPCC, 2014)". Reporting CH_4 emissions from managed wetlands is not mandatory, but if done, parties are encouraged to make use of the 2013 IPCC Wetlands supplement (IPCC, 2014). In the EU, if Member States report these emissions, they report not only restored (rewetted) wetlands but also emissions from drained organic and mineral soils (e.g. peatlands, ditches, etc.). These are not large by magnitude but are large by area in the Nordic countries. According to NGHGI data, in 2021, managed wetlands in the EU, for which emissions were reported under the LULUCF (CRF Table 4(II) and Summary 1.As2 accessible for each EU country), summed up to 0.21 Tg CH_4 yr^{-1}, in comparison to total emissions of ~15 Tg CH_4 yr^{-1}. Furthermore, the NGHGIs do not include any lateral fluxes from inland waters but do include biomass burning anthropogenic emissions reported under the LULUCF sector.

The presented uncertainties in the CH_4 emission levels of the individual countries and the EU are not always reported in a complete and harmonized format, and therefore were calculated applying gap-filling and harmonization procedures that are used to compile the EU GHG inventory reported under UNFCCC (EU NIR, 2023) (see SI and Appendix A1.1 in Petrescu et al., 2023a). The EU uncertainty analysis reported in the bloc's National Inventory Report (NIR) is based on country-level, Approach 1 uncertainty estimates (IPPC, 2006, Vol. 1, Chap. 3) that are reported by EU Member States, previously under Article 7(1)(p) of Regulation (EU) 525/2013 and since 2023 under Article 26(3) and Annex V(Part 1)(m) of the Governance Regulation (EU) 2018/1999.

Non-Annex I countries report their updated NGHGIs to the UNFCCC, including a national inventory report and information on mitigation actions, needs and support received in Biennial Update Reports (BURs). In this study, Brazil, China, Indonesia, India and the Democratic Rep. of Congo (DR Congo) were investigated. For Brazil, information from its fourth BUR (Brazil, 2020) was used, giving both total and sectoral split emission values for years 1994, 2000, 2010, 2012, 2015 and 2016. For China, information from its second BUR Tables 2-10, 2-13, 2-14, 2-15, and 2-16 was used (China, 2019). The information was available for both total and sectoral split emission values for 1994, 2005, 2010 and 2014. Uncertainties for 2014 are available in Table 2-12. Indonesia submitted its third BUR in 2021 (Indonesia, 2021). Indonesian total sectoral CH_4 emissions time series as reported by the 2nd BUR (2001-2016) were revised in the 3rd BUR (2000 and 2019, Table 2). For 2017 and 2018, only the agricultural CH_4 emissions were detailed by the 3rd BUR (Fig. 2-24), but the total emissions for these two years were not reported. Uncertainty for 2019 activity data and emission factors (EFs) are the same as reported in the 2nd BUR (2018). The overall uncertainty of Indonesia's National GHG inventory with agriculture and LULUCF (including peat fires) for 2000 and 2019 were approximately 20.0% and 19.9%, respectively. A much smaller uncertainty, 10.4 % for 2000 and 13.8 % for 2019, occurred when the forestry and land use sector (including forest fires), was excluded from the analysis, pointing to the high uncertainty of emissions from forest fires in Indonesia. The DR Congo submitted its first BUR in 2022, and we used timeseries reported for 2000-2018 (Table 12 Congo, 2022). India has submitted three BURs and information on sectoral CH_4 emissions are in each of them only for one year. We compiled information for 2010 from the first BUR (India, 2016), for 2014 from the second BUR (India, 2018) and for 2016 from the third and latest BUR (India, 2021).

2.3. Other CH_4 data sources and estimation approaches

The CH_4 emissions in the EU and non-Annex I countries used in the atmospheric inversions and anthropogenic and natural emissions estimates from various BU approaches and inventories (i.e., UNFCCC CRFs and BURs) covering specific products, sectors and activities are summarized in Table 1. The data and the detailed description of most products (Tables S1 and S2, Supplementary Information) span the period from 1990 to 2021, with some of the data only available for shorter periods. The estimates are available both from peer-reviewed literature and from unpublished research results from the VERIFY and $CoCO_2$ projects (Supplementary Information, SI) and in this work they are compared with NGHGIs reported in 2023 (time series for all (Annex I) or some years (non-Annex I) of the 1990-2021 period). The BU anthropogenic sources are from UNFCCC NGHGIs and three global inventory datasets/models: EDGARv7.0, FAOSTAT/PRIMAP-hist 2.4 and GAINS. In this synthesis, FAOSTAT (Tubiello et al., 2022; FAO, 2023) data includes estimates for all economic sectors: Energy, Industrial Processes and Products Use (IPPU), Waste and Other, which are sourced from the PRIMAP-hist v2.4 dataset (Gütschow et al., 2022) to build emissions indicators on agrifood systems and on the entire economy. Emission totals from the agrifood domain are computed following the Tier 1 methods of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for NGHGIs. Agrifood systems emissions in FAOSTAT are largely based on FAO crop, livestock and land-use statistics (Tubiello et al., 2022; FAO, 2023). They are complemented with activity data from the UN Statistics Division (UNSD), the International Energy Agency (IEA) and with geospatial information on drained organic soils and biomass fires (Conchedda and Tubiello, 2020; Prosperi et al., 2020).

The analysis focuses on both total and sectoral or partitioned information from both BU and TD estimates. As detailed in Table 1, not all inversions distinguish between sources but in the following sections we discuss comparability between BU and TD for both total and partitioned results.

Table 1: Sectors included in this study and data sources providing estimates for these sectors. CAMS stands for Copernicus Atmosphere Monitoring Service. References to data products are found in Table 2 Petrescu et al., 2023a and Table S1 and S2, SI.

Anthropogenic (BU)[1] CH_4	Natural (BU)[2] CH_4	Regional TD CH_4	Global TD CH_4
1. Energy: UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT/PRIMAP-hist 2.4	Wetlands **EU**: JSBACH-HIMMELI **Global**: LPJ-GUESS	**No partitions – total emissions** FLEXkF_v2023	**Totals and** **partitioned emissions:**
2. Industrial Products and Products in Use (IPPU): UNFCCC NGHGI (CRFs and BURs), EDGAR v7.0, FAOSTAT/PRIMAP-hist 2.4	Peatlands, mineral soils: **EU**: JSBACH-HIMMELI **Global**: LPJ-GUESS	CIF-FLEXPARTv10.4 CIF-CHIMERE	MIROC4-ACTM (control and OH varying runs) CAMSv21r1 (NOAA and NOAA_GOSAT runs)
3. Agriculture: UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT	Inland waters fluxes **EU**: lakes, rivers and reservoirs (RECCAP2)		TM5-4DVAR (TROPOMI)
4. LULUCF: UNFCCC NGHGI (CRFs and BURs) and FAOSTAT	**Global:** lakes and reservoirs ORNL DAAC		CTE-CH_4 (GCP2021)
5. Waste: UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT/PRIMAP-hist 2.4	Geological fluxes updated activity (see SI) Biomass burning (GFEDv4.1s)		CEOS (GOSAT) GEOS-Chem CTM (TROPOMI) for USA only)

note: Not all models have a version id. Those that have, are used in previous syntheses (Petrescu et al., 2021 and 2023a).

We define natural sources as all sources which do not belong to the anthropogenic partition: wetlands, geological, termites, ocean, inland waters, soils and biomass burning(Table 2). The BU natural components for the EU were computed as the sum of the VERIFY products (biomass burning, inland waters and undisturbed peatlands plus mineral soils (as described in Petrescu et al., 2021 and 2023) and geological emissions (Etiope et al. 2019 updated for the VERIFY project). For the seven non-EU emitters, the BU natural fluxes are the sum of wetland emissions (LPJ-GUESS), lake and reservoir emissions (ORNL DAAC), biomass burning emissions

[1] For consistency with the NGHGI, here we refer to the five reporting sectors as defined by the UNFCCC and the Paris Agreement decision (18/CMP.1),the IPCC Guidelines (IPCC, 2006), and their Refinement (IPCC, 2019a), with the only exception that the latest IPCC Refinement groups together Agriculture and LULUCF sectors in one sector (Agriculture, Forestry and Other land Use - AFOLU).

[2]The term **natural** refers here to unmanaged natural CH_4 emissions (peatlands, mineral soils, geological, inland waters and biomass burning) not reported under the anthropogenic UNFCCC LULUCF sector.

(GFED4.1s) and geological emissions (updated activity, SI). The TD natural global estimates were calculated as the sum of all natural partitions reported by the inversions. Adjustments were made to have a consistent comparison between partitions, adding the missing ones from the BU estimates (Table 4). The error bar on the TD natural represents the range of the min/max between inversion estimates.

The total regional TD estimates (for EU) and their uncertainties were calculated as the mean and min/max range between FLEXkF_v2023, CIF-FLEXPART and CIF-CHIMERE inversions (see Priors table in Petrescu et al., 2023b). For the USA, we considered the optimized emissions from the GEOS-Chem CTM (based on TROPOMI data for 2019) from Nesser et al. (2023), with the range from the eight members of the inversion ensemble shown as uncertainty (Table 2 in Nesser et al., 2023).

For all countries, the total global TD inversion estimates (time series) and uncertainties were calculated over the period 2015-2021 using the mean and min/max between CTE-GCP2021, MIROC4-ACTM both runs, CAMS v21r1 (both runs), and TM5-4DVAR (TROPOMI based). CEOS (GOSAT) provided an estimate only for 2019.

The units used in this paper are metric tons (t) [1kt = 10^9 g; 1Mt (Tg) = 10^{12} g] of CH_4. The referenced data for replicability purposes are available for download at https://doi.org/10.5281/zenodo.12582667 (Petrescu et al., 2023b). Upon request, the computer code for plotting figures in the same style and layout can be provided. Throughout the paper and mostly for the complex figures, the following ISO3 country codes are used: USA (United States of America), BRA (Brazil), CHN (China), IDN (Indonesia), RUS (Russia), COD (DR Congo) and IND (India). Next to these we also refer to CHE (Switzerland) and AUS (Australia). The European Union consists of 27 Member States, excludes the United Kingdom (UK) and is further abbreviated as EU. All abbreviations are summarized in the SI, Table S5.

3. Results

3.1. NGHGI official reported estimates (UNFCCC)

Figure 1 presents anthropogenic CH_4 emissions reported to the UNFCCC in 2023 from the NGHGI CRFs (EU, USA and Russia) and BURs (Brazil (4^{th} in 2021), China (2^{nd} in 2019), Indonesia (3^{rd} in 2021), DR Congo (1^{st} in 2022) and India (all three BURs). The following section provides additional details for all the countries.

For the *EU*, the total anthropogenic CH_4 emissions in 2021 amount to 14.8 ± 1.8 Tg CH_4 yr^{-1} and represent 12.8 % of the total EU greenhouse gas emissions (in CO_2 equivalents, GWP 100 years, IPCC AR5[3]). CH_4 emissions are predominantly from agriculture (Figure 1, brown), which accounted for 8.3 Tg CH_4 yr^{-1} ± 0.8 Tg CH_4 yr^{-1} or 56 % of the total EU CH_4 emissions in 2021 (incl. LULUCF). Anthropogenic CH_4 emissions from the LULUCF sector are very small for the EU: 0.5 Tg CH_4 yr^{-1} or 3 % in 2021, including emissions from biomass burning. The EU data from Figure 1 shows steadily decreasing trends for all sectors with respect to the 1990

[3] IPCC AR4 GWP 100 values are still used by the Member States in their NGHGI reporting to the UNFCCC.

levels. The reduction in total CH_4 emissions in 2021 with respect to 1990 is 8.9 Tg CH_4 yr^{-1} (37 %) at an average yearly rate of -1%.

In 2021, the *USA* reported anthropogenic CH_4 emissions of 28.3 Tg and, compared to 1990, the reported USA CH_4 emissions show a small decrease of 4.6 Tg CH_4 yr^{-1}, more pronounced for the last two years (2020-2021), with an average reduction rate of -0.5 % per year (Fig. 1 black dotted line). In the USA, the largest share of emissions comes from the energy sector (38%), and next to IPPU and waste, had the highest reductions since 1990 (42%, 34% and 26%, respectively). Emissions from agriculture (35%, the second largest sector) and LULUCF increased 16 % and 23%, respectively. CH_4 emissions have been slowly declining since 1990 but had a notable decrease of 1.5 Tg CH_4 yr^{-1} in 2016 compared to 2015, before increasing again and had a second decreasing trend in 2020 and 2021, possibly due to the COVID pandemic. Overall, reported data indicates that reductions in the USA CH_4 emissions have declined more slowly than that in the EU. The EU also has much lower CH_4 emissions than the US on a per capita basis (Figure 2).

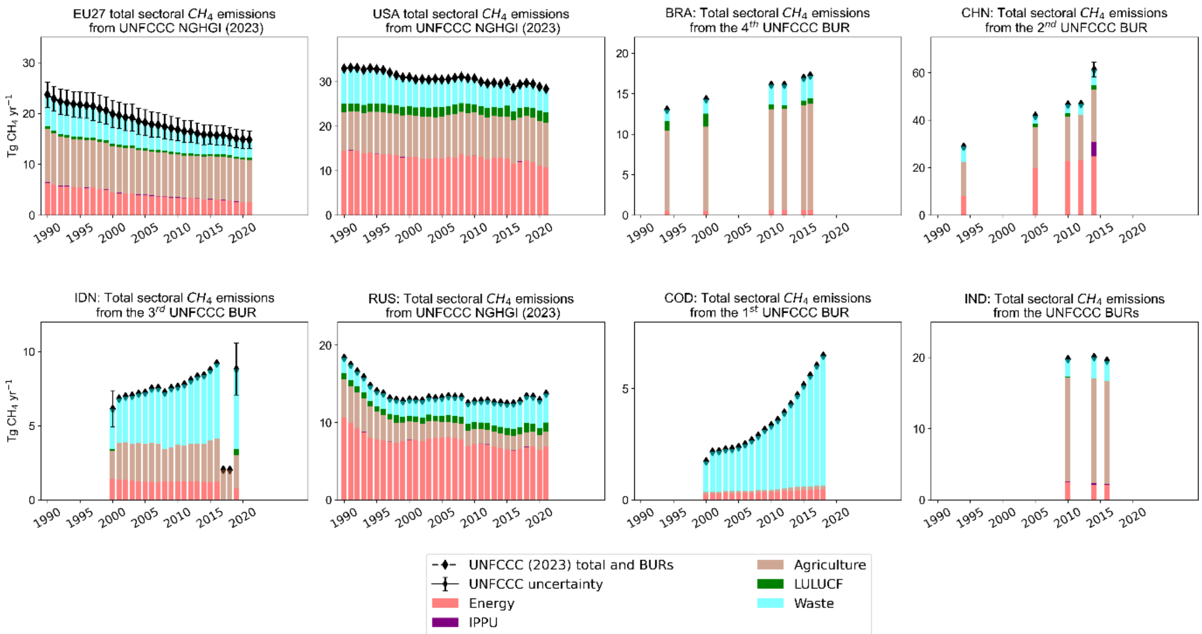

Figure 1: Total and sectoral CH_4 emissions (incl. LULUCF) from the UNFCCC NGHGI (2023) CRFs (EU, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021), DR Congo (1st in 2022) and India (all three BURs: 2016, 2018 and 2021). The relative error on the UNFCCC value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year. Information on Indonesian sectoral CH_4 emissions in 2017 and 2018 are only available for agriculture. The overall uncertainty of Indonesia's National GHG inventory with AFOLU (including peat fires) for 2000 and 2019 were approximately 20.0% and 19.9%, respectively. In 2014, China reported uncertainty as well (min 5.2 % and max 5.3 %).

The trend in total anthropogenic CH_4 emissions in *Brazil* is strongly increasing, with 32.5 % more emissions in 2016 compared to 1994. Given that the Brazilian BUR inventory does not include data between 2001 and 2019, it is difficult to discuss the yearly growth rates. We can only note thatthe agricultural sector (76 % of the total) was the main driver of the growth, followed by the waste sector (16 % of the total). There are only small CH_4 emissions from the energy sector (some oil and gas activities). The Brazilian agricultural CH_4 emissions are the highest of the eight countries on a per capita basis (see Figure 2).

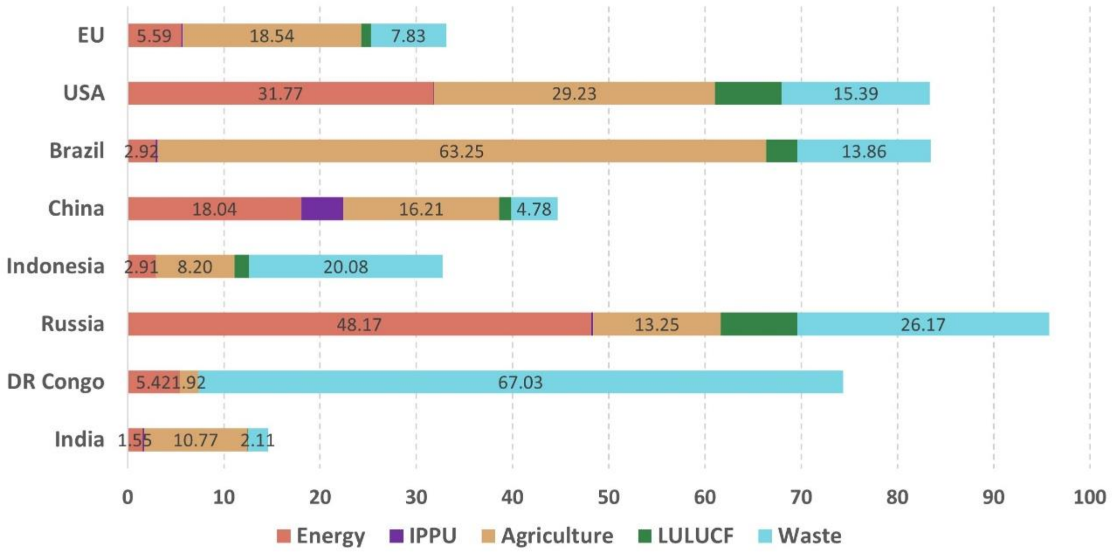

Figure 2: Per capita emissions (kg) intensity per sector based (IPCC, 2006) on reported emissions and population data from the last reported NIRs as follows: 2021 for the EU, USA and Russia, 2016 for Brazil and India, 2014 for China, 2019 for Indonesia and 2018 for DR Congo.

China's total anthropogenic CH_4 emissions are much larger than the emissions reported by many developed countries or the entire EU (see Figure 1), but on a per capita basis it is only fifth of the eight countries considered (Figure 2). China's CH_4 emissions have grown 114% from 1995 to 2014, when they reached 32 Tg CH_4. The highest contributions to China's CH_4 emissions are from energy (40%) and agriculture

(36%). The rapid growth of China's coal demand has important implications for CH_4 emissions from coal mines (Gao et al., 2020). The energy and agriculture sectors have respectively increased by 214 % and 54 % in 2014 compared to 1994.

Indonesia's 3rd BUR data (2000 and 2019) show increasing trends in total anthropogenic CH_4 emissions. The time series 2001-2006 derives from the 2nd BUR submitted in 2018. In 2019, Indonesian CH_4 emissions had increased by +44 % compared to 2000, corresponding to 2.6 Tg $CH_4\,yr^{-1}$, an average yearly increase of 3 %, and the sector which contributes the most to this increase is the waste sector, which nearly doubled its emissions in 2019 compared to 2000. According to Qonitan et al., 2021, the major solid waste source in Indonesia is the household sector, which contributed 44-75% to total waste generated. The composition of municipal waste consists of 44% food waste, 16% paper, and 14% plastics. CH_4 emissions from the other sectors remained nearly constant. For 2017 and 2018 the Indonesian 3rd BUR does not report total emissions other than agricultural emissions, which were taken from the report Figure 2-24. The last data point (2019) shows lower total emissions because it belongs to the revised versions of the (3rd) BUR while the previous data points 2000-2016 belong to the 2nd BUR.

Russia's anthropogenic CH_4 emissions have decreased by -25 % from 1990 to 2021, but most of this decrease happened during the dissolution of the Soviet Union. Since 2000, CH_4 emissions have increased slightly, but remain lower than pre-2000 levels. The decline seen between 1990 and 2000 is primarily due to the agricultural sector (-52 %) and energy (-27 %). At the same time, the waste sector started to increase its emissions (6 %). Between 2001 and 2021, the CH_4 emissions from the agriculture and energy sectors continue to decrease (by 17 % and 11 %, respectively), while the emissions from the waste sector register an additional 76 % increase. IPPU emissions increased by 85 % but remain negligible compared to other sectors. Since the 2000s, LULUCF emissions have also increased, by 53 %.

For its first BUR, *DR Congo* submitted emissions from energy, AFOLU (agriculture plus LULUCF) and waste for 2000-2018. Since 2000, the DR Congo total anthropogenic CH_4 emissions have increased by a factor of four. Most of the CH_4 emissions are reported for the waste sector, and account for 90 % of the total emissions. The high percentage of waste emissions in DR Congo is also seen in the per capita emissions (Figure 2). Assè-Wassa Sama and Berenger (2023) confirm that between 2000 and 2021, CH_4 emissions, which in 2021 represent in DR Congo ~97% of total waste generated emissions, grew at a rate of 4 % yr^{-1}, compared with 2.7 % yr^{-1} for total emissions. This increase was driven by the increase in emissions caused by solid waste disposal (+6.2 %). The CH_4 waste emissions come mainly from the treatment and discharge of wastewater (69 % in 2021, compared with 80 % in 2000), followed by the elimination of solid waste (31 % in 2021, compared with 20 % in 2000). The weight of emissions caused by the elimination of solid waste in the sector's total emissions has nevertheless increased by 11 percentage points between 2000 and 2021 (Assè-Wassa Sama and Berenger, 2023).

Each of *India's* BURs provide detailed information on sectoral CH_4 emissions only for one year. Most of the emissions in India belong to the agriculture sector, amounting to almost 15 Tg CH_4 yr^{-1} (in 2016), representing 74 % of the total anthropogenic emissions. However, with only three years of reported data available, no clear or notable trend is observed.

3.2. NGHGI compared to other bottom-up estimates

Figure 3 shows UNFCCC (CRFs and BURs) estimates from EU and seven non-EU countries compared to global bottom-up inventories. The EU and USA show decreasing trends in emissions from all data sets (except for GAINS in the USA), while all the other countries show increasing trends in all datasets. The match between UNFCCC reported emissions and all other data sources is satisfactory, with a few notable exceptions.

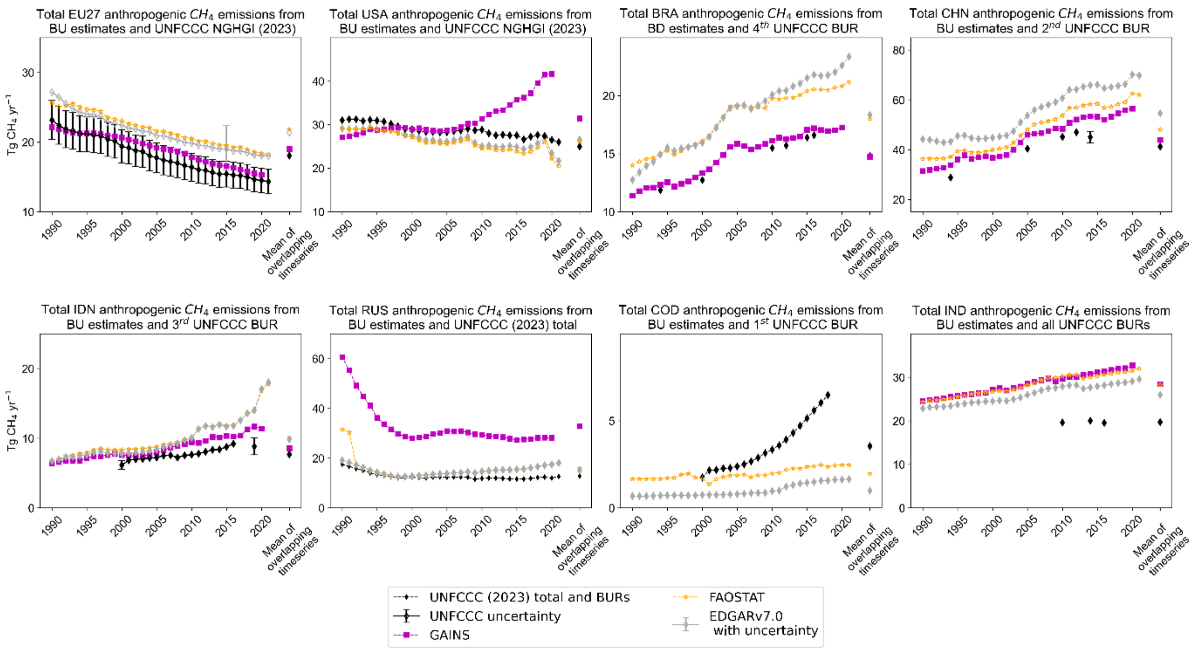

Figure 3: Total anthropogenic CH_4 emissions (excl. LULUCF) from bottom-up (BU) inventories as: UNFCCC NGHGIs (2023) of CRFs (EU, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021), DR Congo (1st in 2022), India (all three BURs:2016, 2018 and 2021) and three other global datasets: EDGARv7.0, GAINS (no IPPU) and FAOSTAT (PRIMAP based, except for AFOLU). The relative error on the UNFCCC value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year. China and Indonesia report uncertainties, for 2014 and 2000 and 2019 respectively (BUR). Total COD UNFCCC BUR emissions do not include IPPU. The EDGARVv7.0 uncertainty is only for 2015 and was calculated according to Solazzo et al., 2021 for EDGARv5.0. The mean of overlapping time series was calculated for 1990-last available year as following: 2021 for UNFCCC NGHGI (2023), EDGARv7.0 and FAOSTAT and 2020 for GAINS.

For the *EU*, the difference between the UNFCCC NGHGI 1990-2020 average and the other three data sets is less than 5 %. As previously discussed, the inventory-based data sources are consistent with each other for capturing recent CH_4 emission reductions, but they are not independent because they use similar methodology with different versions of the same activity data (AD) (Petrescu et al., 2020, Figure 4).

For the *USA*, GAINS reports high emissions after 2010, with strong growth. This divergence is largely found in the energy sector, resulting from the EFs used for conventional gas production as well as for unconventional shale gas extraction, which has increased rapidly since 2006 due to the development of hydraulic fracturing technology (Supplementary Figure S6-1 in Höglund-Isaksson et al., 2020). The high share of emissions from unconventional shale gas can be explained by the GAINS EFs which, in the absence of published factors, are derived from the residual emissions after having subtracted estimated emissions for oil production and conventional gas production from the total upstream emission estimated by Alvarez et al., (2018, Table 1) As Alvarez et al. 2018 do not specify EFs by type of gas produced, GAINSv4 splits it based on activity data from other references, International Energy Agency-World Energy Outlook (IEA-WEO, 2018) and Energy Information Administration (EIA, 2019). On the other hand, the NGHGI EF seems to be too low, and this is reflected by the low oil and gas emissions reported by the Unites States Environmental Protection Agency (USEPA 2017) for 2015, compared to Alvarez et al., 2018 (Supplementary Table S6-3, Höglund-Isaksson et al., 2020). For the USA, total gas production increased by 47 % between 2006 and 2017. Revisions for the agricultural livestock emissions concern updates of AD and reported EFs to statistics from FAOSTAT (2018) and CRFs (UNFCCC 2016; 2018), and a review of available technical abatement options for CH_4.

For *Brazil*, UNFCCC and GAINS report emissions of similar magnitudes and trends. The EDGARv7.0 and FAOSTAT report on average around 23 % more emissions for the 1990-2021 period, but closely follow the NGHGIs trends. The similarity between trends could be explained by the use of the same EFs following Tier-1 IPCC 2006 Guidelines and UNFCCC NIRs (Janssens-Maenhout et al., 2019), while the higher emissions could appear when using different AD information.

For *China* the inventory estimates agree reasonably with the BUR reported data, with EDGARv7.0 showing the highest estimates. According to both GAINS and EDGARv7.0, the primary drivers for growth in Chinese CH_4 emissions are due to a mix of sources, mainly from the IPCC 2006 sector 1.B.1, fugitive emissions from solid fuels activity linked to increased coal mining.

In *Indonesia* the three global datasets agree well up until 2010. From 2010, the third-party datasets show a continued increase in emissions, while the UNFCCC BUR emissions suggest a decline. EDGARv7.0 reports a large increase in emissions from fugitive emissions from solid fuels (coal mining) (IPCC 2006, sector 1.B.1.) at an increased average rate of 19 % per year and has increased by a factor of 152 until 2021 compared to 1990 (Figure 3).

For *Russia*, GAINS emissions are much higher than NGHGIs and the other two data sets due to the revisions of the assumptions on the average composition of the associated gas generated from oil production based on information provided in Huang et al. (2015). The higher emissions in GAINSv4 might be caused by a greater source from venting of associated gas instead of flaring. GAINSv4 estimates a decline in global CH_4 emissions in the first half of the 1990s, primarily a consequence of the dissolution of the Soviet Union and the associated general decline in production levels in agriculture and fossil fuels (see regional emission illustrations in figures S2–1 of the SI). In addition, as described by Evans and Roshchanka (2014) and assumed in Höglund-Isaksson (2017), venting of associated petroleum gas declined significantly in Russia due to an increase in flaring. It is unclear why this happened, but a possible explanation could be that the privatization of oil production in this period meant that the new private owners were less willing to take the security risks of venting and invested in flaring devices to avoid potential production disruptions. This hypothesis is however yet to be confirmed (Höglund-Isaksson et al., 2020). FAOSTAT data for the Russian Federation starts in 1992, but the former USSR statistics were used prior to 1992 without adjustments and this is the cause of the 1990 and 1991 outliers in time series. The slightly increasing trend observed in EDGARv7.0 and FAOSTAT are set by emissions from the energy sector.

For *DR Congo* estimates from GAINS are not available because they only report aggregated emissions from a few African regions. Both FAOSTAT (PRIMAP based) and EDGARv7.0 estimates show similar slowly increasing trends, potentially indicating the use of similar prior statistics (EFs). For non-AFOLU sectors the PRIMAP-hist third party data priority scenario used in FAOSTAT also uses EDGAR data as an input data source explaining similarities in these sectors. On the other hand, UNFCCC BUR data reports a strong increase in emissions, which is due to a rapid growth of CH_4 emissions from the waste sector, by a factor of four until 2018 compared to 2000. This increase happened at an average yearly rate of +8 %, with an initial sharp increase of +30 % between 2000 and 2001. As previously discussed, (section 3.1.) we believe that DR Congo BUR reported waste emissions are improbable and further investigation is needed.

For *India*, all bottom-up global inventories show similar trends and magnitudes of anthropogenic CH_4 emissions. The emissions of CH_4 averaged across EDGARv7.0, GAINS and FAOSTAT are 67% (2010), 68 % (2014) and 65 % (2016) higher than the Indian BURs. All three BU inventories show an averaged steady increase of 1 % yr^{-1} between 1990-2020.

3.3. NGHGIs compared to TD atmospheric-based CH_4 estimates

In Figure 4 we compare the reported TD anthropogenic estimates, after removing natural emissions, with the UNFCCC official reported emissions for the EU and the seven non-EU emitters. The mean column on the right of each chart represents the mean of the overlapping time series (2009-last available year, except for TROPOMI, which was available only for 2018-2020). For the EU, the three regional inversions report total emissions because they do not separate anthropogenic from natural emissions. Therefore, we subtracted from the total the natural emissions as calculated in Petrescu et al., 2023a which amount to 6.6 Tg CH_4 yr^{-1} and are the sum of biomass burning, wetlands, geological and inland water CH_4 emissions. For the global inversions, the anthropogenic estimates were calculated by subtracting from the total fluxes the reported natural partitions as follows: for the two CAMS inversions and TM5-4DVAR (TROPOMI based) the sum of biomass burning and wetlands, for MIROC4-ACTM runs the natural is the represented by the sum of the biomass burning, geologic, ocean, termites, soils and wetlands, for CTE-GCP2021 the sum of the biologic (wetlands + soils) and other (ocean, termites, geological). Because not all inversions report the same partitions, we consider this a coarse comparison, and we detail the harmonization of the natural emissions in the next section (Table 4 and Figure 7). For China, the last BUR is available for 2014, and therefore we used that value.

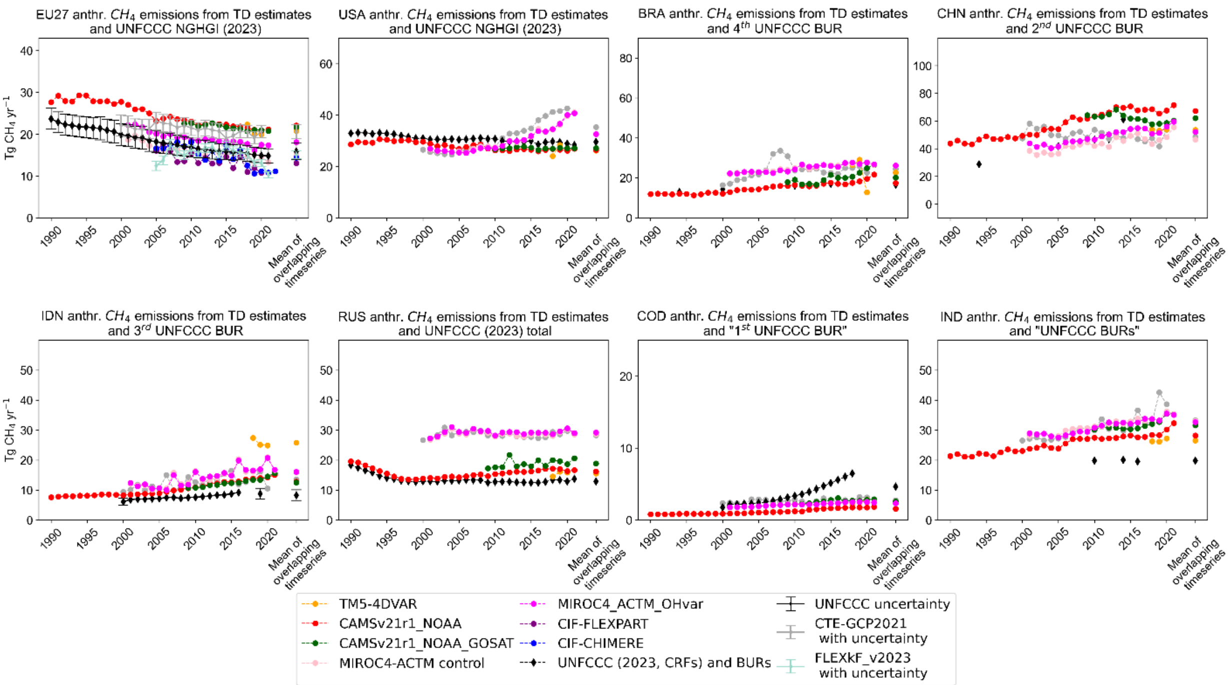

Figure 4: Anthropogenic CH_4 emissions from UNFCCC NGHGI (2023) CRFs (EU, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021), DR Congo (1st in 2022), India (all three BURs: 2016, 2018 and 2021) and TD estimates as following: for EU anthropogenic regional inversions (FLEXkF_v2023, CIF-FLEXPART and CIF-CHIMERE) and for global inversions anthropogenic estimates calculated as total TD minus natural TD reported partitions (TM5-4DVAR, CAMSv21r1_NOAA, CAMSv21r1_NOAA_GOSAT, CTE-GCP2021 and MIROC4-ACTM both runs) products. The relative error on the UNFCCC value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year. China reports uncertainties for 2014 (min 5.2 %, max 5.3 %) and Indonesia reports for 2000 and 2019, 20 % and 19.9 % respectively. Total COD UNFCCC BUR emissions do not include IPPU. The last available years are CIF-CHIMERE (2022), TM5-4DVAR, CIF-FLEXPART and CTE-GCP2021 (2020) and FLEXkF_v2023, MIROC4-ACTM both runs, UNFCCC CRFs, and CAMSv21r1 both runs (2021). The mean of overlapping time series was calculated for 2009-2021, except for TM5-4DVAR (2018-2020).

In the *EU*, the average anthropogenic CH_4 emissions from global inversions for 2009-2021 were 19 Tg CH_4 yr^{-1} with a min-max range of 15-23 Tg CH_4 yr^{-1}, in line with previous estimates published in Petrescu et al. (2021, 2023a) and the recent RECCAP2 European GHG budgets study of Lauerwald et al., 2024. This is consistent with the UNFCCC NGHGI (2023) which report for the same period anthropogenic emissions of 15.8 ± 1.8 Tg CH_4 yr^{-1}, noting the uncertainty ranges of both estimates overlap. There is good agreement in trends, but with inversions showing a larger year to year variability. The regional inversions, for the same period, report averaged emissions of 14 Tg CH_4 yr^{-1} with a min-max range of 13-20 Tg CH_4 yr^{-1}. We note that the regional inversions tend to report slightly lower emissions than the global inversions, closer to the UNFCCC estimates. One reason could be that regional inversions use better-constrained regional observations (e.g. ICOS, not just

NOAA), have higher spatial resolution, and may thus better resolve the transport. However, they may still have problems with the regional boundary conditions.

For the *USA*, averaged over the period 2009-2021, inversions indicate anthropogenic CH_4 emissions of 30 Tg CH_4 yr^{-1} with min-max range of 26-35 Tg CH_4 yr^{-1}, well in line with the UNFCCC NGHGIs (2023) which for the same period report anthropogenic total emissions of 29 Tg CH_4 yr^{-1}. The trends observed in TD products are slightly increasing after 2010, except for CAMS which shows no trend (Figure 4). The striking discrepancy between the trends from CAMS and those from MIROC4-ACTM and CTE-GCP2021 are most likely caused by the increasing oil and gas emissions from the Eastern USA (Permian Basin). The same increasing trend is also captured by GAINS (Figure 3). In their runs, both MIROC4-ACTM and CTE-GCP2021 use oil and gas priors from GAINS, while CAMS uses priors from EDGAR (Figure 3). We discuss further differences in having CTE-GCP2021 run with both EDGAR and GAINS oil & gas prior estimates in the SI.

For *Brazil*, inversions yield an average (range) of anthropogenic CH_4 emissions of 23 (17-27) Tg CH_4 yr^{-1}, slightly higher than the UNFCCC estimate of 16.6 Tg CH_4 yr^{-1}. The two CAMS inversions have trends which match the trend of the UNFCCC reports estimates.

For *China*, approximately 80 % of the CH_4 emission increase (21.5 Tg yr^{-1}) during 2000 – 2015 was from fugitive emissions from coal (mines), consistent with what GAINS and EDGAR report (Figure 3). The TD estimates mostly agree with the BURs, except for CAMS inversions which show 10 to 20 Tg CH_4 yr^{-1} higher emission than the other inversions. Both MIROC4-ACTM runs (control and OH inter-annual variability (IAV) varying run; Patra et al., 2021) are in line with the BURs. Trend wise, all inversions agree on increased emissions after 2019, with a slight decrease after 2013 which picks up again after 2018 seen in all inversion trends.

For *Indonesia*, most TD results agree on the trend and show a slight increase in emissions. A similar trend is also seen by the BURs. However, the CAMS inversions show linear increased trends while the other inversions have a more variable trend. Regarding the East Asian estimates, MIROC4_ACTM inversion simulates higher fluxes compared to the other inversions. Only recently they found that annual total East Asian emissions have lowered more significantly than in Patra et al. (2016) or Chandra et al. (2021), therefore new runs with updated input set-ups are currently being investigated.

For *Russia*, the estimates from MIROC4-ACTM runs and CTE-GCP2021are both in the same range as the BU GAINS estimate (see Figure 2) from 2000 onwards (between 30-40 Tg CH_4 yr^{-1}) but does not show such a strong decrease as GAINS from 1990 to 2000), while CAMS runs report about 10 Tg CH_4 yr^{-1} lower emissions than the other two inversions, matching the UNFCCC estimates. The reason for higher estimates reported by CTE-GCP2021 and MIROC4-ACTM is most likely the use of oil and gas priors from GAINS.

For *DR Congo*, inversions show the same slightly increasing trend, similar to that of UNFCCC BURs, without the abrupt increase after 2010. The inversions appear to confirm the overreported growth in emissions from waste.

For *India*, all the TD anthropogenic estimates agree well on increased trends and magnitudes. In contrast, UNFCCC reporting does not show any trend, but given the insufficient data from BURs, a plausible conclusion cannot be drawn.

3.4. Sectoral attribution of CH_4 emissions in TD products

In some cases, inversions can be used to partition emissions to different sources. Table 2 shows the partitions as originally reported by some of the inversions, which we name here “unharmonized partitions”. A straightforward, direct comparison of the fluxes is not possible because of the different ways each inversion allocates and groups the natural/anthropogenic fluxes. For example, not all inversions report soil fluxes as done by MIROC4-ACTM and CTE-GCP2021 (together with wetlands) or report the biomass burning fluxes separately from anthropogenic emissions (MIROC4-ACTM and TM5-4DVAR). Rice is also sometimes allocated to natural emissions. Termites, oceans and geological fluxes are sometimes reported separately (MIROC4-ACTM) or grouped in “Other” (CTE-GCP2021, TM5-4DVAR). Regarding the anthropogenic emissions, TM5-4DVAR reports them as other, providing a separate partition for rice. Figure 5 shows the UNFCCC NGHGI anthropogenic total reported estimate (diamond) next to all TD estimates. All global inversions report total and disaggregated partitions, while the regional inversions report only the total emissions (green column).

Table 2: Unharmonized partitions originally reported by inverse products:

Inversion	Anthropogenic	Rice	Soils	Wetlands	Ocean	Termites	Geological	Biomass burning	Other
CAMSv21r1 (both runs)	Yes (as Other)	Yes	No	Yes	Yes (in Other)	Yes (in Other)	No	Yes	Yes**
MIROC4-ACTM (control and OH var)	Yes ((agr, waste, oil/gas, biofuel, coal)	Yes (in agr.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes (separated)
CTE-GCP2021*	Yes (agr, waste, fossil fuel, biofuel, biomass burning)	Yes (in agr.)	Yes (BIO)		Yes (as Other)	Yes (as Other)	Yes (as Other)	as anthr.	Yes (Ocean, Termites, Geological)
CEOS (GOSAT)	Yes (livestock, rice, waste, coal, oil, fire)	as anthr.	No	Yes	No	No	Yes (seeps)	as anthr.(but separate)	only seeps
TM5-4DVAR (TROPOMI)	Yes (as Other)	Yes	No	Yes	Yes (as other)	Yes (as other)	Yes (as Other)	Yes	Yes**
GEOS-Chem CTM (TROPOMI for USA)	Yes (livestock, oil/gas, landfills, wastewater, Other anthro. (rice)	as other anthr.	No	Yes	Yes (as Other)	Yes (as Other)	Yes (as Other)	Yes (as Other)	Yes***

*CTE-GCP2021 partitions refer to anthropogenic, bio and other.

** In TM5-4DVAR (similar to the CAMSv20 set-up and CAMSv21r1), the "Other" partition includes anthropogenic sources except for the rice paddies. It also includes the small fluxes from termites, oceans, soil sink, geological etc.). More details on priors are found in Petrescu et al., 2023b, Priors table.

***Named Other biogenic

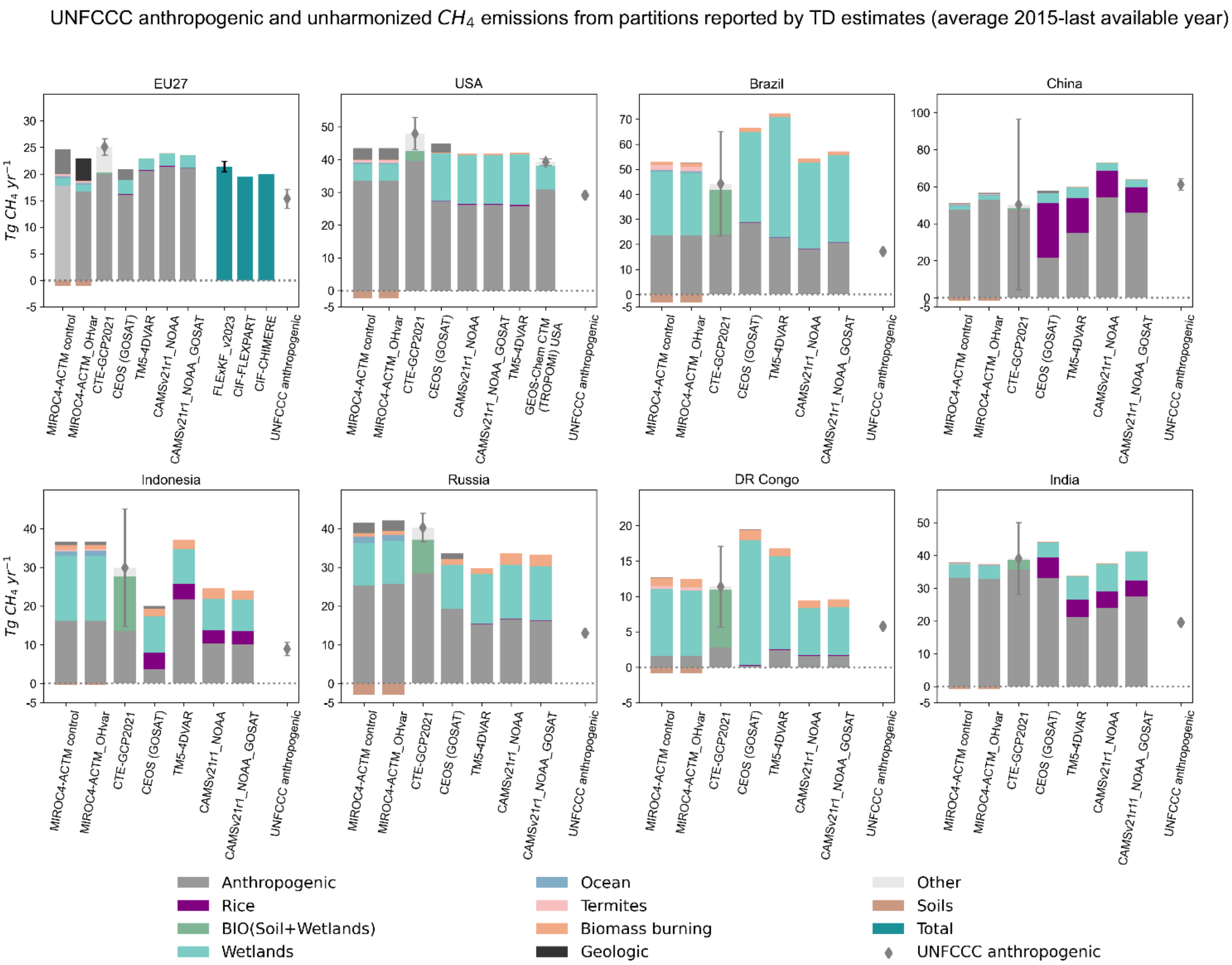

Figure 5: Total (green) and disaggregated anthropogenic and natural CH_4 emissions from TD estimates compared to UNFCCC NGHGI (2023) anthropogenic emissions (incl. LULUCF) (diamond) for the EU and seven global emitters outside the EU (USA, Brazil, China, Indonesia, Russia, DR Congo and India). The UNFCCC anthropogenic value represents the sum of all five IPCC sectors (Energy, IPPU, Agriculture, LULUCF and Waste). The partitions reported by the TD global inversions are detailed in Table 2. The relative error on the UNFCCC CRF value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year (see Petrescu et al., 2023a, Appendix). China value and uncertainties (min 5.2 %, max 5.3 %) are for 2014 only and Indonesia uncertainties for 2019, 19.9 %. For the USA CEOS (GOSAT) we used the Nessar et al., 2023 total uncertainty of min 1.1 and max 1 Tg yr^{-1}. CTE-GCP2021 provides uncertainties for each partition, but here the uncertainty of the total flux is shown. FLEXkF_v2023 reports the relative uncertainty (%) of the posterior emissions. The plotted data represents the average between 2015 and last available year as follows: CIF-CHIMERE (2022), TM5-4DVAR, CIF-FLEXPART and CTE-GCP2021 (2020) and FLEXkF_v2023, MIROC4-ACTM both runs, UNFCCC CRFs, and CAMSv21r1 both runs (2021). GEOS-Chem CTM (TROPOMI) USA reports only for 2019 (Nesser et al., 2023).

Since the different models define sectors differently, also whether they are natural or anthropogenic, harmonization is required to make them comparable. CTE-GCP2021 reports the net natural land-biosphere flux

"BIO flux" (soil+wetlands), while other inversions report wetlands and soil separately. Rice emissions are sometimes a part of the agriculture component (anthropogenic partition) (MIROC4-ACTM, CTE-GCP2021) while CEOS (GOSAT) and GEOS-Chem CTM (USA TROPOMI) report separate partitions for rice in anthropogenic emissions, while CAMS reports rice separate from anthropogenic and natural. Same for the biomass burning - CTE-GCP2021 and CEO report it as part of anthropogenic emissions, while GEOS-Chem CTM as part of Others. The rest of the inversions report it separately; this different allocation makes comparisons for these two sources challenging. To facilitate comparisons between all TD products, we aggregated and harmonized the partitions in three main categories, as summarized in Table 3 and Figure 6. The dark green columns in Figure 6 show the total flux for regional EU inversions which did not report partitions.

Table 3: Harmonized partitions from inverse products:

Inversions	**Anthropogenic + Rice + Biomass burning**			**Soils + Wetlands**		**Other (Ocean + Termites + Geological)**		
	Anthropogenic	**Rice**	**Biomass burning**	**Soils**	**Wetlands**	**Ocean**	**Termites**	**Geological**
CAMSv21r1 (both runs)	= Other	Yes	Yes	No	Yes	Yes	Yes	Yes
MIROC4-ACTM (control and OH var)	Yes ((agr (livestock + **rice**), waste, oil/gas, biofuel, coal)	In agr.	Yes, summed to anthr.	Yes	Yes	Yes	Yes	Yes
CTE-GCP2021*	Yes (agr (**rice** is in), waste, fossil fuel, biofuel, biomass burning)	in agr.	In anthr.	Yes (BIO)		Yes (Other)		
CEOS (GOSAT)	Yes (livestock, rice, waste, coal, oil, fire)	In anthr.	In anthr.	No	Yes	No	No	Yes
TM5-4DVAR (TROPOMI)	Others + rice+ BB	In anthr.	Yes, summed to anthr.	In Other	Yes	Yes	Yes	Yes
GEOS-Chem CTM (TROPOMI) USA	Yes	In anthr.	In other biogenic	No	Yes	Yes	Yes	Yes

*CTE-GCP2021 partitions refer to Anthropogenic, Bio and Other. Other fluxes are imposed

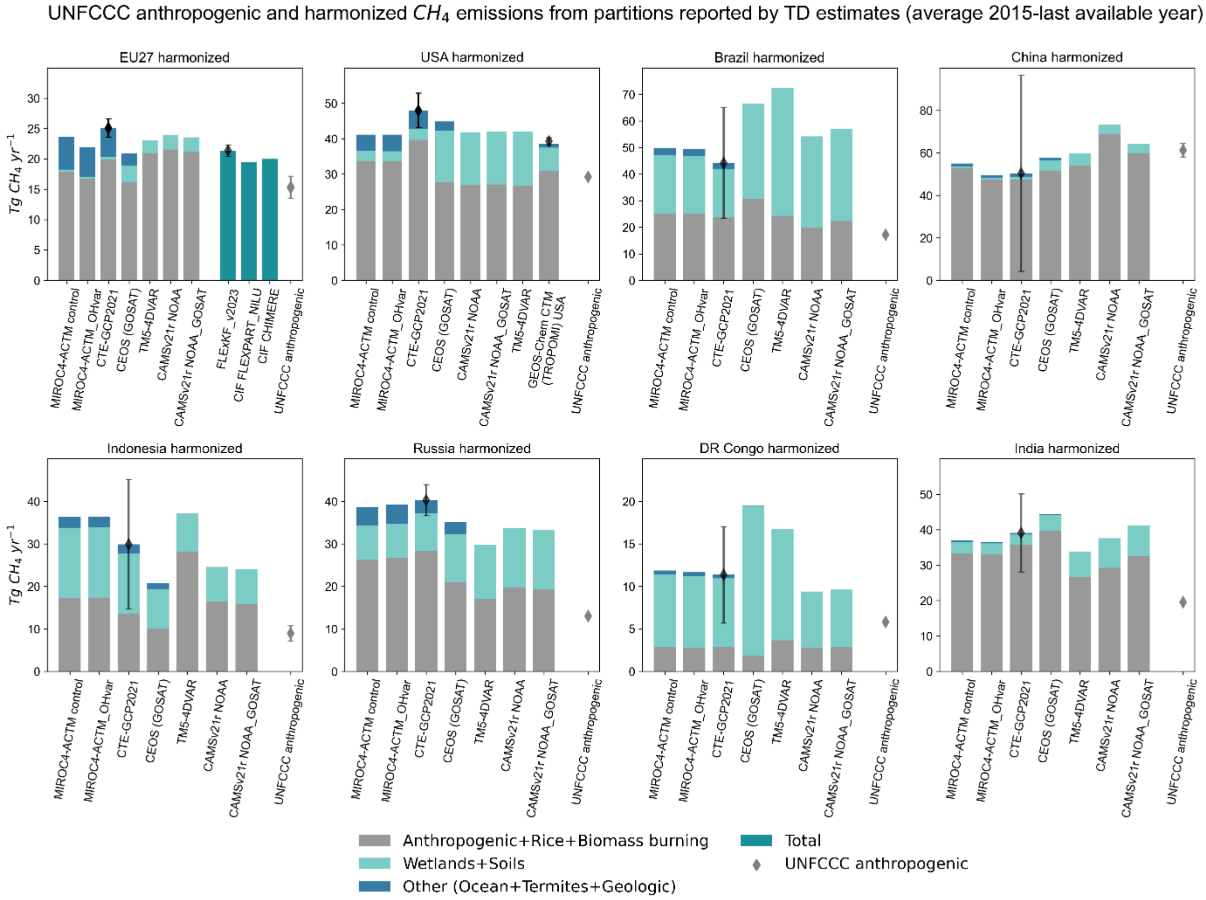

Figure 6: Total (green) and disaggregated anthropogenic and natural CH_4 emissions from TD estimates compared to UNFCCC NGHGI (2023) anthropogenic emissions (incl. LULUCF) for the EU and seven global emitters (USA, Brazil, China, Indonesia, Russia and DR Congo). The UNFCCC anthropogenic value represents the sum of all five IPCC sectors (Energy, IPPU, Agriculture, LULUCF and Waste). The partitions reported by the TD global inversions are harmonized and detailed in Table 3. The relative error on the UNFCCC CRF value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year (see Petrescu et al., 2023a, Appendix). In 2014, China UNFCCC value and reported uncertainties (min 5.2 % and max 5.3 %) are for 2014 while Indonesia reported uncertainties for 2019, 19.9 %. India UNFCCC value is for 2016. CTE-GCP2021 provides uncertainties for each partition, but here we plotted the uncertainty of the total flux. FLEXkF_v2023 reports the relative uncertainty (%) of the posterior emissions. The plotted data represents the average between 2015 and last available reported year as follows: CIF-CHIMERE (2022), UNFCCC CRFs, TM5-4DVAR, CIF-FLEXPART and CTE-GCP2021 (2020) and FLEXkF_v2023, MIROC4-ACTM both runs, and CAMSv21r1 both runs (2021). GEOS-Chem CTM (TROPOMI) USA reports only for 2019 (Nesser et al., 2023).

3.5. Comparison of BU and TD CH_4 estimates

Figure 7 summarizes the total CH_4 fluxes for the EU and the seven global emitters as following: BU anthropogenic sources disaggregated per sector, BU natural emissions, TD natural emissions from regional and global inversions, and total emissions from global TD estimates (see 2.3 and SI for description of all data products). This figure brings all the estimates together to demonstrate the reconciliation process.

Inversions currently report in a way that makes comparison between BU natural and TD natural sources difficult. TD products differ in the sources they report (Table 2) or they allocate them to different categories. We consider natural the following sources: biomass burning, soils, oceans and termites (often reported by inversions under category "Other"), wetlands, geological and lakes & reservoirs (or freshwaters). Due to lack of information, biomass burning emissions were considered among the natural sources, recognizing that in regions like tropical forests, some of these events are influenced by human intervention. To make the products from Figure 7 comparable, we added the missing BU information from TD, and vice-versa, presented in hatched pattern. In this way, comparison between BU and TD natural emission estimates is consistent regarding the "apples to apples" comparison, but became "apples of different flavors" (see Table 4):

Table 4: BU and TD natural partitions as presented in Figure 7:

Product name	**TD natural partitions**			
	Reported	Missing* (not in priors	Not reported**	Missing was added from:
CAMSv21r1_NOAA	BB, wetlands, "Others" include anthropogenic and was not used	lakes and reservoirs, geological	termites, oceans, soil sink	DAAC lakes and reservoirs, geological, updated in this study (see SI)
CAMSv21r1_NOAA_ GOSAT	BB, wetlands, "Others" include anthropogenic and was not used	lakes and reservoirs, geological	termites, oceans, soil sink	DAAC lakes and reservoirs, geological, updated in this study (SI)
MIROC4-ACTM control	BB, wetlands, oceans, termites, soils, geological	lakes and reservoirs		DAAC lakes and reservoirs
MIROC4-ACTM_OHvar	BB, wetlands, oceans, termites, soils, geological	lakes and reservoirs		DAAC lakes and reservoirs
CTE-GCP2021	soils + wetlands (BIO), termites and oceans	lakes and reservoirs	BB, geologic	DAAC lakes and reservoirs
CEOS (GOSAT)	Fires (BB), Seeps and wetlands	termites, oceans, soils, lakes and reservoirs		MIROC4-ACTM (termites, oceans and soils), DAAC lakes and reservoirs
TM5-4DVAR (TROPOMI)	BB and wetlands	lakes and reservoirs, geological,	termites, oceans, soil sink	DAAC lakes and reservoirs, geological, updated in this study (see SI)
Product name	**BU natural partitions**			
		Reported	Not reported**	Added from
Biomass burning **Lakes and reservoirs** **Wetlands**		GFEDv4.1s DAAC LPJ-GUESS	soils termites oceans	MIROC4-ACTM

Geological	Geological emissions updated in this study (SI)		

note: in TD products termites, oceans emissions are imposed from existing literature

* missing = not in the priors, presented as hatched pattern in the figure “\\\”

**Not reported = data not available, presented as hatched pattern in the figure “///”

For an easier visual comparison and reconciliation between BU and TD estimates, we added the mean of the BU anthropogenic estimates (off-white), underneath the BU and TD natural estimates. To note that for some countries (e.g. Russia, DR Congo) this area might look like subtracted from the BU natural estimates, but this is due to the sign convention used in this study (sink = negative and source = positive). In most cases, the missing soil sink emissions are represented as a downward area.

We note that for most countries, the sum of the anthropogenic and natural components matches those of the TD global total estimates. This gives confidence that, to a certain extent and albeit with inconsistencies between products, BU anthropogenic emission estimates are accurate and consistent with the observation-based estimates and can be used to reconcile with the atmospheric-based estimates. We note from Figure 7 that in all Annex I countries (EU, USA, Russia) and China, TD and BU natural emissions are consistent with each other, after including the missing sources, as detailed in Table 4. For Brazil and DR Congo, the gap between the two natural components is highly significant, while less for Indonesia and India. We hypothesize that mapping of the wetland extent might cause these inconsistencies.

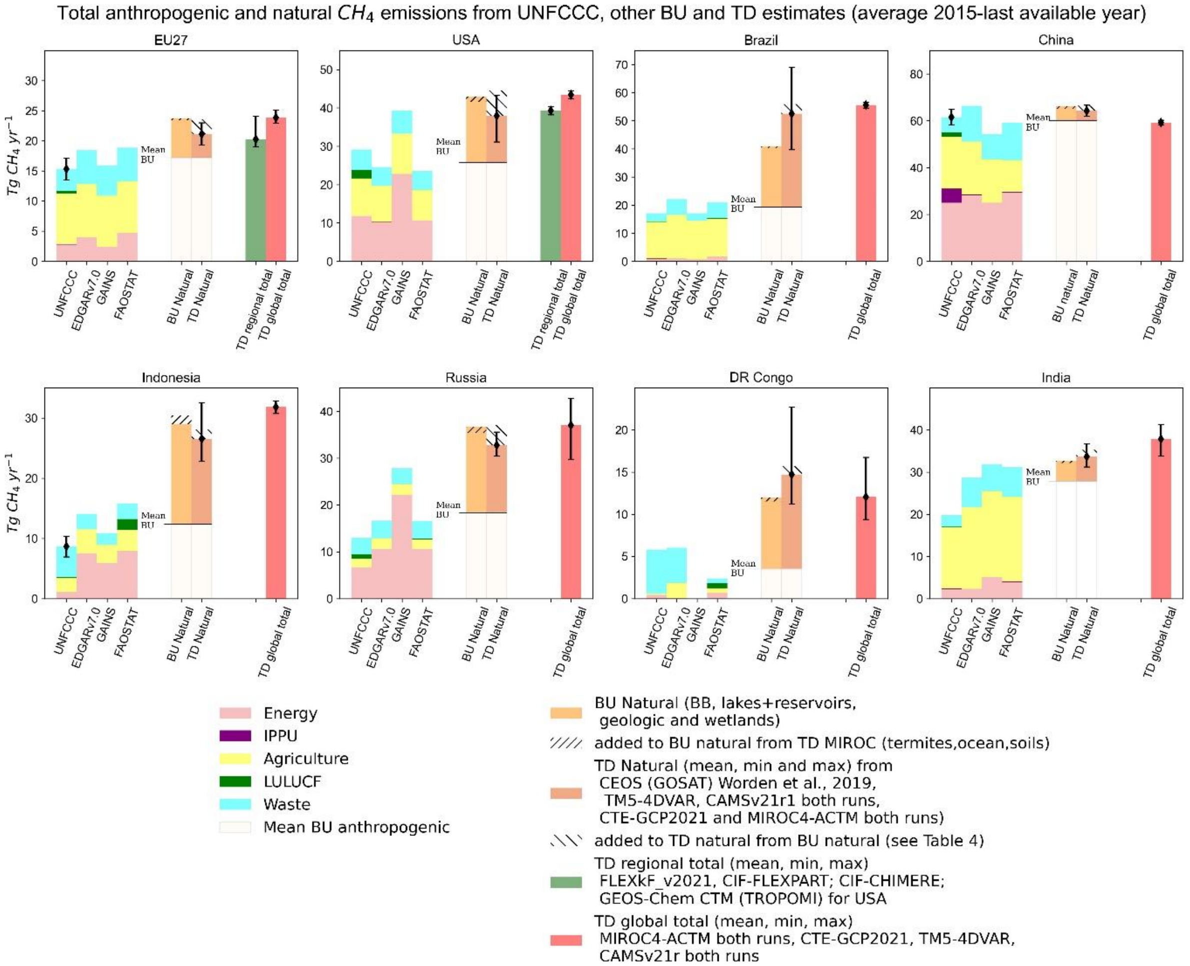

Figure 7: Total anthropogenic and natural CH_4 emissions from BU and TD estimates presented as average of 2015-last available year for EU and seven global emitters (USA, Brazil, China, Indonesia, Russia, DR Congo and India). The BU anthropogenic estimates belong to: UNFCCC NGHGI (2023) CRFs and BURs (incl. LULUCF) as totals and sectoral shares, EDGARv7.0, GAINS and FAOSTAT/PRIMAP-hist. The relative error on the UNFCCC CRF value represents the NGHGI (2023) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year (see Petrescu et al., 2023a, Appendix). In 2014, China reported an uncertainty of min 5.2% - max 5.3%. The BU Natural emissions for the EU are the sum of the VERIFY products (biomass burning, inland waters, geological and peatlands plus mineral soils as described in Petrescu et al., 2021 and 2023a, Appendix A2.1). For the seven non-EU emitters, the BU Natural fluxes are the sum of wetland emissions (LPJ-GUESS), lakes and reservoirs fluxes (ORNL DAAC, Johnson et al., 2022), geological (updated activity in SI) and biomass burning emissions (GFED4.1s). The TD natural global estimates are presented in Table 1. The uncertainty on the TD natural emissions is the min/max of all estimates. To both BU and TD estimates, missing (as not reported or not includedin the priors) was added (see Table 4). The natural emissions have been plotted starting at the mean of the BU anthropogenic estimates, to retain comparability across the natural emission estimates, but also compare with the total TD estimates. The total regional TD estimates (for EU) belong to the mean and min/max of FELXkF_v2023, CIF-FLEXPART and CIF-CHIMERE and for USA GEOS-Chem CTM (TROPOMI) for the year 2019 (Nesser et al., 2023). The total global TD inversions represent the average of the 2015-last available year

of the mean and min/max of CTE-GCP2021, MIROC4-ACTM both runs, CAMS v21r both runs and TM5-4DVAR. The last available years are 2022 for CIF-CHIMERE, 2021 for EDGARv7.0, FAOSTAT, MIROC4-ACTM both runs, UNFCCC CRFs, and CAMSv21r1 both runs, and 2020 for CIF-FLEXPART and CTE-GCP2021. TM5-4DVAR partitioned data is only available between 2018 and 2020.

However, Figure 7 should be interpreted with caution because in Europe, natural emission priors come from regional ecosystem model simulations, where drained peatland, drainage ditches areas, and pristine areas are lumped together. Therefore, if both LULUCF sector and natural BU emissions are included in the total budget estimation, there is some overlap and possible double counting. Especially, ecosystem model estimates of 'soil sink' or 'inundated soil emissions' may overlap with NGHGI managed peatland forest soil category (or agricultural soils). The separation of emissions into different categories requires further clarification together with inventory makers. Furthermore, it should be assessed which emissions should be called natural and which anthropogenic (e.g., LULUCF, agriculture) by inversions.

4. Challenges comparing bottom-up and top-down estimates

An off-the-shelf comparison of BU and TD estimates is not possible, with a variety of adjustments needed for comparability, often without the necessary data. Broadly speaking, inversions have not necessarily been designed to compare directly to NGHGIs. A valid comparison should have consistent system boundaries and perform a full uncertainty analysis to determine whether differences between estimates are statistically significant given the constraining observational data.

The two most common issues limiting comparability are geographic scope and system boundaries (Petrescu et al., 2021, 2023; McGrath et al., 2023, Andrew 2020; Grassi et al., 2018). The **geographical scope** of inverse modelling versus inventory estimates should be controllable, but it can be challenging for small countries or coarse inversions. Inversions are generally performed on a spatial grid and require aggregation, in line with how official NGHGIs are reported (EEA, 2013). Inconsistent **system boundaries** have implications in comparing the inventory- with inversions-based estimates for **source attribution**, e.g., anthropogenic vs. natural. Most emission inventories aim at estimating anthropogenic emissions, while most inversions estimate both anthropogenic and natural emissions. This is a particularly important issue for CH_4 where, globally, natural emissions are of similar magnitude as anthropogenic emissions, with larger variations at regional scales, mainly due to seasonality (i.e. wetlands). Thus, methods are needed to separate the anthropogenic flux from the total flux (Deng et al. 2022, and above section 3.4). Similar issues arise with fossil CO_2 (Andrew 2020) as different datasets can report different emission sources. Standardization procedures, such as The Community Inversion Framework (CIF; Berchet et al., 2021), may help resolve some of these issues.

When comparing inventory- and inversion-based emissions, there are difficulties in analyzing **trends** due to different time scale **variability**. Inventory-based approaches report emissions at the annual level, but often do not consider interannual variations. Further, the Paris Agreement is set around five-yearly Global Stocktakes, which indicates a desire to average trends, prioritizing the multi-annual trend over IAV, canceling out extremes from both weather and socio-economic fluctuations. Inversion models, on the other hand, include variations over a wide range of timescales, but in particular for IAV (e.g. OH and weather) that remains challenging to assess.

For an effective comparison, inversion-based estimates need to have IAVs statistically removed to make comparisons with NGHGIs easier (e.g., 5-year or 10-year averages or trend analysis). Additionally, averages of ensembles of inversions may mask underlying differences and trends in individual inversions. Many research projects make use of multi-model ensembles (Saunois et al., 2020; Deng et al. 2022, Lauerwald et al., 2024, Zhang et al., 2024). From a scientific perspective, the model ensemble is often considered a more robust estimate of the mean and uncertainty, as often individual estimates make errors due to some limitations and biases, while in an ensemble, these errors are averaged out. From an inventory perspective, individual model comparisons may be more efficient, as various input variables or processes can be compared directly to the inventory. Currently, most inventory comparisons in UNFCCC NGHGI (e.g. UK, Switzerland) use single-model comparisons.

A strength of inversions is that they provide high temporal and spatial resolutions, which are not directly capitalized when comparing with inventories. CH_4 from the fossil-fuel industry can contribute to large releases to the atmosphere over a short period of time, given the large number of uncontrolled emission point sources in oil and gas (O&G) and coal production areas worldwide (Jackson et al., 2020). Such processes include leakage from landfills, spontaneous events from oil and gas production activities, so-called uncontrolled gas well blasts etc. (Jacob et al., 2016, 2022). These uncontrolled events are difficult to include in the national inventories leading to a potential underestimate of emissions (Massakkers et al., 2016, 2022). Recently, under the $CoCO_2$ project (https://coco2-project.eu/) a hot-spot satellite detection interactive map (Published studies on hot spot detection (CO2, CH4) - uMap (openstreetmap.fr)) was released as a user-centric interface featuring published studies on hot-spot detection between 2010 and 2021. It allows for advanced filtering by year, gas, activity, geographical zone, and country.

A key challenge when comparing inversions with NGHGIs is ensuring independence from the assumed prior emissions. A more valid comparison between inversions is made when all inversions use the same **priors**. In this context, we define as priors input data in the form of atmospheric observations (e.g. satellite retrievals, ground-based observation networks (ICOS)) and/or bottom-up emissions datasets (e.g. EDGAR, GAINS) used as input parameters to the inverse models. A key issue is the prior emission estimate. Theoretically, a constant emission prior could be used, but this would require a dense observational network. Because of sparse observations, inversion modelers assess how far observations have shifted the prior emissions to the posterior emissions, preferably incorporating a full uncertainty analysis. The posterior emissions depend to a varying extent on the prior that was used; the extent of this dependency is determined by the number of observations used in the inversion, by how the observations relate to the emissions (governed by atmospheric transport) and by the uncertainties assigned on the prior emissions and the observations. Thus, better quantified uncertainties for the prior emissions would lead to more robust inversions. Whereas the comparison of an inversion with NGHGIs or other inversions would be made more robust by having more information on how dependent the posterior estimate is on the prior. This stresses the need for more systematic in-situ data necessary to produce adequate prior data (Bastviken et al., 2022) and synthesized atmospheric observations with their uncertainties to robustly constrain the inversions.

It is not generally clear how inventory uncertainties can be compared to inversion uncertainties; however, it is important that both methods provide comprehensive **uncertainty estimates**. The prior emissions used as input into an inversion model should have robust uncertainty estimates, particularly with correlations in space and time. This allows a full inversion system to better characterize how observations reduce uncertainty when estimating the posterior estimate. Very few inversions routinely report this information. The inventory-based emission estimate will additionally have uncertainty estimates, though these statistics may not be sufficiently robust for verification purposes (National Academies of Sciences, Engineering, and Medicine 2022). There are often offsets in inversion models, because of systematic inconsistencies between observations and chemistry-transport models, which may make trends more robust than instantaneous estimates. Though, estimating uncertainty in trends also requires understanding the correlation structure in time.

A key challenge for comparisons between NGHGI and independent estimates is to understand the reasons for differences. In the case of BU comparisons, obtaining sufficient activity data and emission factors should enable an accurate reconciliation of different estimates. However, in practice, it is often not possible to obtain the necessary data. For inversions it is more complex. Often a close collaboration may be needed between the inversion modeler and NGHGI team (e.g. UK NIR). If an inversion indicated a different trend in agricultural CH_4 emissions, it is necessary to track down if this is a real difference or artifact of the inversion system. After this, the spatial and temporal data in the inversion could be useful to the NGHGI team to locate what is causing the difference. Many of the comparisons we show in this article ultimately remain comparisons, with detailed reconciliations likely requiring intensive country-level case studies.

5. Data availability

Data files reported in this work which were used for calculations and figures are available for public download at https://doi.org/10.5281/zenodo.12582667 (Petrescu et al., 2023b). The data are reachable with one click (without the need for entering login and password), with a second click to download the data, consistent with the two click access principle for data published in ESSD (Carlson and Oda, 2018). The data and the DOI number are subject to future updates and only refer to this version of the paper. The raw gridded data is available upon request, directly from the data providers, as detailed in the Supplementary Information, Table S2.

6. Conclusions

We analyzed data from both anthropogenic and natural CH_4 fluxes, from both BU and TD observation-based estimates (Table 1). BU estimates show that the largest sectors depend on the country: agriculture (EU, Brazil, India), energy (US, China, Russia), and waste (Indonesia, DR Congo). The inversions attribute most of the fluxes to the anthropogenic emissions, with tropical countries having a larger share of natural emissions (wetlands). The EU and the seven other large emitters analyzed here contribute an anthropogenic emission of 173 Tg CH_4 yr^{-1} (sum of last UNFCCC reported year, Figure 1,2), representing roughly half of the total global anthropogenic emissions (386 Tg CH_4 yr^{-1}) reported by EDGARv7.0 in 2021. For comparison, the average of the anthropogenic component from the atmospheric global inversions (MIROC booth runs, CTE-GCP2021, CEOS and CAMS booth runs) is 181 Tg CH_4 yr^{-1} (Figure 5).

We performed comparisons to the UNFCCC NGHGIs using the BU and TD data. Comparisons between UNFCCC and BU products (Figure 3) reveal some deviations, particularly related to assumptions on gas/oil emissions (e.g., GAINS for Russia and the USA) and waste (e.g., Indonesia, DR Congo). It is more challenging to compare BU and TD estimates, due to different attribution to source activities (Table 2 and Figure 5) and different priors used in the simulations (Petrescu et al., 2023b, Priors Table). The comparison between UNFCCC and the TD estimates (Figure 4) agrees largely with the findings of Deng et al. (2022) who applied different methodologies to calculate natural emissions. In most cases, the gap between the anthropogenic BU fluxes from inventories and total TD fluxes can be largely explained by the natural fluxes (Figure 7). It is difficult to draw definitive conclusions on emissions trends seen by inversions, as the adjustments for natural emissions and IAV and seasonal variability might strongly influence trends. Despite this, given that, in most cases, the UNFCCC BURs reports are incomplete for the non-Annex I parties (China, Indonesia, DR Congo) it is important to acknowledge that the TD estimates might become a useful way to complement inventories and play a role in the validation of the BU estimates.

There is still a pressing need for reporting of uncertainties in both prior and posterior emissions, even if some TD inversions do report it as the standard deviation of ensemble members (CTE-GCP2021 and FLEXkF_v2023, Figure 4). The use of a variety of priors across different inversion systems can also inhibit comparability with inventories and between inversions. Generally, inversions are still ill-constrained by observations (only 60 sites globally plus satellites) and the prior flux uncertainty for each of the 54 regions is large. Therefore, the monthly results could be more ill-constrained than the annual totals. Even if comparisons between CH_4 inversion estimates and NGHGIs are currently uncertain because of the spread in the inversion results, TD inversions inferred from atmospheric observations represent partly independent data against which inventory totals and trends can be compared, considering the most encountered issues discussed in section 4.

7. Appendix

All the information regarding models/methods descriptions is available in the Supplementary Information (SI) file. Appendices A1 and A2 in Petrescu et al., 2023a contain detailed information about Table 1 products. Further information on new products together with references and contact details are found in Tables S1 and S2 in SI.

The tables with priors used by all the products and the matrix highlighting the comparability issues identified in section 4 are found in the Zenodo data repository, Petrescu et al., 2023b.

Supplementary Information (link)

Author contributions

AMRP designed research and led the discussions; AMRP wrote the initial draft of the paper and edited all the following versions; GPP drafted the initial version of section 4, edited the final version of this manuscript, contributed to the revised version and advised on the context; PP processed all the original EU data submitted to the VERIFY portal; RLT, SH, BM, DaB, RL, PKP, AT, RMA, LHI, FNT, GC and JG edited and gave consistent comments and suggestions to the initial manuscript; DaB, RL and RMA provided input to the final revised version; all co-authors are data providers and contributed to subsequent versions of the manuscript by providing specific comments and information related to their data in the main text, providing as well product descriptions for the Supplementary Information file.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Earth System Science Data.

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