CoCO2

Prototype system for a Copernicus CO_2 service

Scientific review article on carbon budgets for the year 2021

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WP6

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Author(s): Roxana Petrescu (VU), Matthew McGrath, Philippe Peylin (LSCE), Glen P. Peters, Robbie Andrew, Richard Engelen, et al.

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CoCO2: Prototype system for a Copernicus CO_2 service

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Contact:
ECMWF, Shinfield Park, Reading, RG2 9AX,
richard.engelen@ecmwf.int

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1 Executive summary

We provide below two separate executive summaries corresponding to the draft articles for the CH_4 and CO_2 flux syntheses that are provided in Appendix A and B.

CH_4

Knowledge of the spatial distribution of the fluxes of greenhouse gases and their temporal variability as well as flux attribution to natural and anthropogenic processes is essential to monitoring the progress in mitigating anthropogenic emissions under the Paris Agreement and to inform its Global Stocktake. This study provides a consolidated synthesis of CH_4 emissions using bottom-up (BU) and top-down (TD) approaches for the European Union (EU27) and six global major emitters and updates earlier syntheses (Petrescu et al., 2020, 2021a, 2023). The work integrates updated emission inventory data, process-based model results, data-driven sector model results, inverse modelling estimates, and, whenever, available their uncertainties. Whenever possible, it extends the period up until 2021. BU and TD products are compared with European National GHG Inventories (NGHGI) reported by Parties under the United Nations Framework Convention on Climate Change (UNFCCC) in 2023. Results of six top global emitters are included. By comparing NGHGIs with other approaches, the activities included are a key source of bias between estimates e.g., anthropogenic and natural fluxes, which, in atmospheric inversions, are sensitive to the prior geospatial distribution of emissions. Over the studied period, which covers a sufficiently robust number of overlapping estimates, and most importantly the NGHGIs, the total CH_4 emissions in EU27 show a steady decreasing trend compared to 1990, which is needed for the EU's climate reduction targets. For global emitters, reductions in CH_4 emissions are mostly seen for Annex I parties, while non-Annex I parties show increased emissions.

In the EU27, the anthropogenic BU approaches are directly comparable, accounting for mean emissions over 2015 to last available year of 18 Tg CH_4 yr^{-1} for EDGAR v7.0 (last year 2021), 16 Tg Tg CH_4 yr^{-1} for GAINS (last year 20202) and 19 Tg CH_4 yr^{-1} for FAOSTAT (last year 2020), similar to the NGHGI estimates of 15.6 ± 2 Tg CH_4 yr^{-1}. TD inversions estimates give higher emission estimates, as they also detect natural emissions. Over the same period, the median of high-resolution regional TD inversions report a mean emission of 20 Tg CH_4 yr^{-1}, while the median of six coarser-resolution global TD inversions result in emission estimates of 24 Tg CH_4 yr^{-1}.. The magnitude of natural emissions (peatland and mineral soils, natural rivers, lakes and reservoirs, geological and biomass burning) together account for 6.6 Tg CH_4 yr^{-1} and could represent the gap between NGHGI anthropogenic BU results and TD total inversions.

For the top global emitters, the situation strongly differs between Annex I and non-Annex I countries, Anthropogenic CH_4 estimates from UNFCCC BURs show large differences in non-Annex I countries compared to atmospheric-based estimates. It poses an important reservation on the status of the global CH_4 pledge and future implementation of Global Stocktake initiative, not only from the availability of data, but also from its quality point of view.

By comparing TD and BU methods defined in this study, we hope to steadily engage more parties in using atmospheric methods in complementing their UNFCCC inventories. New steps involving analysis at finer temporal resolutions and estimation of emissions over intra-annual timescales, of great importance for CH_4, may help identify sector contributions to divergence between prior and posterior estimates at the annual/inter-annual scale. Even if currently comparison between CH_4 inversions estimates and NGHGIs is uncertain because of the spread in the inversion results, TD inversions inferred from atmospheric observations represent the most independent data against which inventory totals can be compared. With anticipated improvements in atmospheric modelling and observations, as well as modelling of natural fluxes, TD inversions may arguably emerge as the most powerful tool for verifying emissions inventories for CH_4, and other GHGs. The referenced datasets related to figures are visualized at https://doi.org/10.5281/zenodo.7553800 (Petrescu et al., 2023).

CO_2

Quantification of land surface-atmosphere fluxes of carbon dioxide (CO_2) fluxes and their trends and uncertainties is essential for monitoring progress of the EU27 bloc as it strives to meet ambitious targets determined by both international agreements and internal regulation. This study provides a consolidated synthesis of fossil sources (CO_2 fossil) and natural sources and sinks over land (CO_2 land) using bottom-up (BU) and top-down (TD) approaches for the European Union (EU27), updating earlier syntheses (Petrescu et al., 2020, 2021b; McGrath et al., 2023). Given the wide scope of the work and the variety of approaches involved, this study aims to answer essential questions identified in the previous syntheses and understand the differences between datasets, particularly for poorly characterized fluxes from managed ecosystems. The work integrates updated emission inventory data, process-based model results, data-driven sectoral model results, and inverse modelling estimates, covering the period 1990-2021 to the extent possible. BU and TD products are compared with European National Greenhouse Gas Inventories (NGHGIs) reported by Parties including the year 2021 under the United Nations Framework Convention on Climate Change (UNFCCC). The uncertainties of the EU27 NGHGI were evaluated using the standard deviation reported by the EU Member States following the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and harmonized by gap-filling procedures. Variation in estimates produced with other methods, such as atmospheric inversion models (TD) or spatially disaggregated inventory datasets (BU), originate from within-model uncertainty related to parameterization as well as structural differences between models. By comparing NGHGIs with other approaches, key sources of differences between estimates arise primarily in activities. System boundaries and emission categories create differences in CO_2 fossil datasets, while different land use definitions for reporting emissions from Land Use, Land Use Change and Forestry (LULUCF) activities result in differences for CO_2 land.

For CO_2 fossil emissions, after harmonizing estimates based on common activities and selecting the most recent year available for all datasets (2019), the UNFCCC NGHGI for the EU27 accounts for 2920 ± 41 Tg CO_2 yr^{-1} (797 ± 11 Tg C yr^{-1}), while eight other BU sources report a median value of 2730 [2690,2750] [25th,75th percentile] Tg CO_2 yr^{-1} (744 [733,751] Tg C yr^{-1}). Two top-down inversions of fossil emissions currently available accounts for 3090 Tg CO_2 yr^{-1} (843 Tg C yr^{-1}) for the same year, a value close to that of the NGHGI, but for which uncertainty estimates are not yet available. **For the net CO_2 land fluxes,** during the only period where all datasets overlap (2015-2018), the NGHGI accounted for -80 [± 28 Tg C yr^{-1} while seven other BU approaches reported a mean sink of -59 [-103, -38] Tg C yr^{-1} and a 18-member ensemble of dynamic global vegetation models (DGVMs) reported -93 [-183,-34] Tg C yr^{-1}. The mean of three TD regional ensembles combined with one non-ensemble inversion of -105 Tg C yr^{-1} over the same period has a slightly smaller spread (0th-100th percentile of [-197,-73] Tg C yr^{-1}), and was calculated after removing land-atmosphere CO_2 fluxes caused by lateral transport of carbon (crops, wood trade and inland waters) resulting in increased agreement with the NGHGI and bottom-up approaches. Results at the sub-sector level (Forestland, Cropland, Grassland) show generally good agreement between the NGHGI and sub-sector-specific models, but results for a DGVM are mixed. Overall, for both CO_2 fossil and net CO_2 land fluxes, we find current independent approaches are consistent with the NGHGI at the scale of the EU27. We conclude that CO_2 emissions from fossil sources have decreased over the past 30 years in the EU27, while large uncertainties on net uptake of CO_2 by the land surface prevent trend identification. In addition, a gap on the order of 1000 Tg C yr^{-1} between CO_2 fossil emissions and net CO_2 uptake by the land exists regardless of the type of approach (NGHGI, TD, BU), falling well outside all available estimates of uncertainties. However, uncertainties in top-down approaches to estimate CO_2 fossil emissions remain uncharacterized and are likely substantial. The data used to plot the figures are available at a dedicated web site (https://webportals.ipsl.fr/VERIFY/FactSheets/) where the synthesis plots for EU27 as well as for all individual countries are accessible.

2 Introduction

2.1 Background

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. To independently assess the progress of EU27 countries towards their targets (cut its emissions by at least 55% by 2030 and the Green Deal to reach zero net emissions of greenhouse gases in 2050), the European Commissions (EC) indicated that an objective way to monitor anthropogenic CO2 emissions and their evolution over time was needed. Such a capability would provide consistent and reliable information to support informed political and decision-making processes. The European Commission is therefore establishing an operational observation-based anthropogenic CO_2 emissions monitoring and verification support capacity (CO2MVS) as part of its Copernicus Earth Observation programme.

As all countries in the EU27 are Annex I Parties to the United Nations Framework Convention on Climate Change (UNFCCC), they prepare and report national GHG emission inventories (NGHGIs) on an annual basis. These inventories contain annual time series of each country's GHG emissions from the 1990 base year until two years before the year of reporting and were originally set to track progress towards their reduction targets under the Kyoto Protocol (UNFCCC, 1997). Annex I NGHGIs are reported according to the Decision 24/CP.19 of the UNFCCC Conference of the Parties (COP) which states that the national inventories shall be compiled using the methodologies provided in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

In addition to the NGHGIs, other research groups and international institutions produce independent estimates of national GHG emissions with two approaches: atmospheric inversions (top-down, TD) and GHG inventories based on the same principle as NGHGIs but using slightly different methods (tiers), activity data, and/or emissions factors (bottom-up, BU).

CH_4

The latest data from the NOAA Global Monitoring Laboratory (GML) network reported in 2021 the highest value of CH_4 atmospheric concentration to record, accounting for 17 parts per billion (ppb), reaching 1895.7 ppb, the largest annual increase recorded since systematic measurements began in 1983, and 162 % greater than pre-industrial levels. From NOAA's observations, scientists estimate global methane emissions in 2021 are 15% higher than the 1984-2006 period (https://gml.noaa.gov/ccgg/trends_ch4/).

As part of the CO2MVS concept, which combines information from different observational datasets and from existing knowledge about emissions together with detailed computer models of the Earth system, observations can also provide information about the processes that are responsible for the exchange of CH_4 between the Earth's surface and the atmosphere such as human activities (i.e., CH_4 leaks from the oil and gas production areas). The signal of anthropogenic emissions in the variables is weak compared to those from natural sources, therefore, advanced data assimilation methods (D8.6 A Catalogue of published studies on hotspot detection of emissions for CO2 and CH4 | CoCO2: Prototype system for a Copernicus CO2 service (coco2-project.eu)) can then make adjustments to emissions that are consistent with information from observations and constrained by the physical knowledge encapsulated in the models.

Following the global context introduced above, this report updates the recently published European synthesis from Petrescu et al., 2023, and deepens analysis on sources of anthropogenic and natural CH_4 emissions in the EU27 and six top global emitters. It examines both Annex I and non-Annex I estimates from observation-based bottom-up process-based models and inversions-based top-down approaches (satellite observations) by identifying and explaining differences with official inventory reports submitted by parties to the UNFCCC. In depth attention is given to methodological issues identified in the Decision Support System (DSS; D8.4 CoCO2 report) and previous studies (e.g., Petrescu et al., 2020, 2021, 2023) when comparisons are performed between approaches. The criteria for choosing the six countries were mainly based on location and the importance / magnitude of natural emissions which might help explain differences with TD products. By using multiple methodologies, uncertainties can be estimated by looking at the range in both emissions and trends. This will also allow strengthening the robustness of such comparison exercises when using independent atmospheric observations in estimating trends and patterns for regional/national CH_4 emissions.

CO_2

The rise in CO_2 concentrations in recent decades is caused primarily by CO_2 emissions from fossil sources. Globally, fossil emissions in 2021 (excluding the cement carbonation sink) totalled 10.1 ± 0.5 Gt C yr^{-1} (34.8 ± 1.8 Gt CO_2 yr^{-1}) (Friedlingstein et al., 2022). In contrast, global net CO_2 emissions from land use and land use change (LULUC, primarily deforestation) estimated from bookkeeping models and dynamic global vegetation models (DGVMs) were estimated to have a small decreasing trend over the past two decades, albeit with low confidence (Friedlingstein et al., 2022). This decrease, however, is almost an order of magnitude less than the growth in fossil emissions over the same period, and therefore the total fossil and net LULUC flux has still increased.

The current CO_2 work has a strong focus on the EU27, and therefore sits within the context of recent legislation passed by the European Parliament concerning commitments for the LULUCF sector to achieve the objectives of the Paris Agreement and the reduction target for the Union (EU, 2018a and the proposed amendments, EU, 2021a). The TD and BU methods discussed in the draft article below (Appendix B) include the most up-to-date publicly available spatially explicit information, which can help provide a quality check and increase public confidence in NGHGIs. It covers dozens of distinct datasets and models, in addition to the individual country submissions to the UNFCCC of the EU Member States.

A comprehensive investigation of detailed differences between all datasets is beyond the scope of this paper, though systematic analyses have been previously made for specific sectors (e.g., AFOLU - previous synthesis to this work - Petrescu et al., 2021b, and McGrath et al., 2023) and by the Global Carbon Project CO_2 syntheses (e.g., Friedlingstein et al., 2022). The current manuscript (Appendix B), given the focus on a single region ("Europe") with extensive data coverage, dives into more detail than the Global Carbon Budget, including sector-specific models related to LULUCF (e.g., Forest land, Grassland, Cropland) and making heavy use of the EU27 NGHGI in an effort to build mutual trust in the various approaches. Compared to McGrath et al. (2023), the current work updates datasets, methods, and uncertainties and discusses a few country-level examples (using the VERIFY website; VERIFY-CoCO2 Synthesis Plots, 2023). A focus is on covering up to the year 2021 as possible.

McGrath et al. (2023) is the most comprehensive comparison of the NGHGI and research datasets (including both TD and BU approaches) for the EU27+UK to date. The current paper narrows the focus to the EU27, given the departure of the United Kingdom from the European Union, and improves estimates compared to the previous version. Official NGHGI emissions are compared with research datasets, including necessary harmonization of the latter on total emissions to ensure consistency. Not all models/inventories provided an update to include the year 2021, and, therefore, for the non-updated datasets the previously published time series are shown. The dataset/analysis assembled in this paper will be further used in a scientific paper in the ESSD journal (submitted before the end of the CoCO2 project), as an update of the previous synthesis (McGrath et al., 2023).

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverables

This document is the deliverable D6.2 "Scientific review article on carbon budgets for the year 2021", that was split in two parts (Appendices): Part-1 for the CH_4 budget and Part-2 for the CO_2 budget, including both land fluxes and fossil fuel emissions. Part-1 summarises the CH_4 budget for EU27 and six global major emitters, following on the published scientific synthesis form the VERIFY project (Petrescu et al., 2021a and 2023). The Part-2 summarises the CO_2 budgets for Europe, mainly for the EU27 with a few additional examples from individual countries. It is a draft of a scientific article following a previous CO_2 synthesis performed at the end of the VERIFY project (McGrath et al., 2023; under review since Jan 2023). The overall objective of this deliverable is to compare flux estimates provided by national greenhouse gas inventories submitted by Member States to the UNFCCC (referred to as "NGHGI") to observation-based flux estimates including top-down atmospheric inversions as well as bottom-up process-based and data-driven model estimates. The particular objective of this deliverable is to update the previous synthesis, focussing on the additional 2021 year and including updated fluxes for the different approaches and products of the CoCO2 project.

2.2.2 Intended audience

Since this deliverable is aimed at country-level emission estimates, the primary audience is national inventory agencies and policy makers at both national and regional levels, but this will also more broadly encompass the European Commission CO_2 Monitoring Task Force (CO2MVS), the Copernicus Atmospheric Monitoring System (CAMS) implementation team, and those in the European Commission responsible for the CO2MVS or its components.

A secondary audience is the scientific community generating many of the data products in the CO2MVS, and user communities interested in smaller spatial and temporal details. The relevant spatial scales are mainly regions (European Union), countries, cities, and stakeholders (industry, satellite companies).

2.2.3 Work performed in this deliverable

To complete this deliverable, we have performed the following work:

- gathered the most recent estimates of CH_4 and CO_2 land and fossil flux estimates from NGHGIs, atmospheric regional and global inversions, process-based regional and global (from the TRENDY inter-comparison) model simulations and data-driven model simulations.
- processed them in order to produce new synthesis plots comparing different sectors/categories (fossil, land use change, forest, etc.) aggregated at country level (for all countries in the world but more specifically for European countries using EU-specific flux estimates).
- updated the joint VERIFY - CoCO2 projects website (https://webportals.ipsl.fr/VERIFY/FactSheets/) to display the different synthesis plots for all countries with a user friendly and interactive interface (see description in the CO_2 article in Appendix B).
- synthesised the results in this deliverable focussing the analysis on the last year of the flux estimates, 2021, and focussing on EU27.
- carry out informal discussions with scientists and users.
- collected the bottom-up and available satellite-based CH4 global data for major emitters

2.2.4 Deviations and counter measures

There is no deviation with respect to the scope and scientific content of the deliverable. However, there is a delay in the production of this deliverable (5 months) due to delays in the production and processing of the different flux estimates. We note also that the scientific articles associated to this deliverable will only be finalised and submitted towards the end of 2023, given that i) the previous CH_4 synthesis is just published (Petrescu et al., 2023), ii) the previous CO_2 synthesis (covering up to 2020) is still under review in Earth System Science Data (McGrath et al., 2023, ESSD - The consolidated European synthesis of CO2 emissions and removals for EU27 and UK: 1990–2020 (copernicus.org), iii) the UNFCCC official submissions for 2021 and associated uncertainties will only be available this summer and iv) few data providers will still need to submit before the summer updated results to include 2021.

3 Result of the CH_4 and CO_2 synthesis

We refer the reader to the above executive summary and the content of the two draft articles provided in Appendix A and B, in order to avoid unnecessary duplication of text.

4 Conclusion

We provide below short conclusions for the CH_4 and CO_2 synthesis, respectively, based on the more detailed summary and conclusion provided in the two draft articles in Appendix.

CH_4

For the CH_4 study we conclude that it is challenging to reconcile between BU and TD estimates, due to different priors used in the simulations (see Appendix A, Table A2). Also challenging is the comparison between different TD products due to the difficult procedure to allocate fluxes to different activities and sectors/sources. Despite comparability issues highlighted in section 2.3 and Table A1 of the CH_4 article (see Appendix A), we find comparison between UNFCCC – BU valid. The deviations from BU estimates compared to the NGHGIs are mainly due to assumptions regarding gas/oil emissions (e.g., GAINS for Russia, USA).

The comparison between UNFCCC – TD is acceptable, even if, in most cases the UNFCCC BURs report underestimated CH_4 fluxes for non-Annex I parties (China, Indonesia, DR Congo) compared to the total TD estimates, but this is due to the reporting of the anthropogenic component only. We also note that the gap between the anthropogenic and total TD fluxes can be mostly explained by the inclusion of the natural fluxes. For CH_4 emissions, we make comparisons with a variety of inventory-based estimates and inversions. CH_4 emissions have increased in the last three decades but have declined in the USA and EU (regulations) and Russia (dissolution of the Soviet Union). For the inventories, divergences between data sets can generally be attributed to different methodology and tiers used by each of the investigated inventories, when data is available to make comparisons (such as activity data and emission factors). The use of a variety of priors across different inversion systems can also inhibit comparability with inventories and between inversions.

For the inversions, the general magnitudes and trends agree, but uncertainties are too large to be more specific. However, the split in anthropogenic and natural components helped explain some differences. For a more robust analysis, more detail is needed on prior and posterior uncertainties, to help identify statistically significant differences between datasets.

CO_2

For the CO_2 study, the scope of the analysis has been narrowed to the European Union but providing some additional observations on individual countries. CO_2 fossil emissions dominate the anthropogenic CO_2 flux in the EU27, regardless of the approach employed and irrespective of uncertainties. Fossil CO_2 emissions are more straightforward to estimate than ecosystem fluxes due to combustion being easier to model and parameterize at large scales, assuming accurate fossil data is available. A suite of eight BU methods for fossil CO_2 emissions are within the uncertainty of the NGHGI when methods are harmonized to include similar categories. Multiple results from one TD model, a regional European inversion system (CIF-CHIMERE) using different proxy sources, show broad agreement with the BU estimates. However, this initial TD inversion is not yet capable of distinguishing the minor differences between the various BU estimates and does not yet quantify uncertainties. A substantial decrease in the level of uncertainty of the inverse modelling system is expected in the near-term with the large-scale deployment of observation networks dedicated to detecting fossil fuel emissions (e.g., with launch of the CO_2M[1] satellite mission in 2026).

The LULUCF sector in NGHGIs is composed of six land use categories. Of these, Forest land provides the most important contribution to the net CO_2 land flux in the EU27, followed by Cropland and Grassland. HWP and “Land converted to settlements” also have non-negligible contributions, and changes in HWP strongly influence variations in decennial mean net LULUCF fluxes for the region. Top-down inversions are capable of simulating net CO_2 fluxes to the atmosphere, but cannot yet attribute them between different categories. Uncertainties in the inversion results are primarily due to uncertainties in atmospheric transport modelling, boundary conditions, technical simplifications and uncertainty inherent to the limitation of the observation network.

Observation-based BU estimates of LULUCF provide large year-to-year flux variability, contrary to the NGHGI, primarily due to the effect of varying meteorology. In the framework of periodic NGHGI assessments, the choice of a reference period or the use of a moving window to calculate the means may thus be critical to smooth out high inter-annual variability and facilitate comparisons. One can also imagine incorporating IAV into the NGHGIs through the use of annual anomalies of emission factors calculated from Tier 3 observation-based approaches (either BU or TD). TD estimates also show very large inter-annual variability.

Currently, the EU27 reports a sink for LULUCF and forest management will continue to be the main driver affecting the productivity of European forests for the next decades (Koehl et al., 2010), shown as well by the domination of Forest land CO_2 fluxes to the LULUCF sector in the NGHGI. The EU Forest sink is projected to decrease in the near future (Vizzarri et al., 2021). Consequently, for the EU to meet its ambitious climate targets, it is necessary to maintain and even strengthen the LULUCF sink (EU, 2020). Understanding the evolution of the CO_2 land fluxes is critical to enable the EU27 to meet its ambitious climate goals.

5 References

EU: Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG, 2018a.

EU: Procedure 2021/0201/COD, COM (2021) 554: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review, https://eur-lex.europa.eu/procedure/EN/2021_201, 2021a.

[1] CO_2M: Copernicus Anthropogenic Carbon Dioxide Monitoring, https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., Arneth, A., Arora, V. K., Bates, N. R., Becker, M., Bellouin, N., Bittig, H. C., Bopp, L., Chevallier, F., Chini, L. P., Cronin, M., Evans, W., Falk, S., Feely, R. A., Gasser, T., Gehlen, M., Gkritzalis, T., Gloege, L., Grassi, G., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Jain, A. K., Jersild, A., Kadono, K., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lindsay, K., Liu, J., Liu, Z., Marland, G., Mayot, N., McGrath, M. J., Metzl, N., Monacci, N. M., Munro, D. R., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pan, N., Pierrot, D., Pocock, K., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Rodriguez, C., Rosan, T. M., Schwinger, J., Séférian, R., Shutler, J. D., Skjelvan, I., Steinhoff, T., Sun, Q., Sutton, A. J., Sweeney, C., Takao, S., Tanhua, T., Tans, P. P., Tian, X., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G. R., Walker, A. P., Wanninkhof, R., Whitehead, C., Willstrand Wranne, A., Wright, R., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J., and Zheng, B.: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

IPCC 2006. IPCC Guidelines for National Greenhouse Gas InventoriesInventories, Prepared by the National Greenhouse Gas Inventories Programme. Edited by H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Japan: IGES. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Koehl, M., Hildebrandt, R., Olschofsky, K., Koehler, R., Roetzer, T., Mette, T., Pretzsch, H., Koethke, M., Dieter, M., Abiy, M., Makeschin, F., and Kenter, B.: Combating the effects of climatic change on forests by mitigation strategies, Carbon Balance and Management, 5, 8, https://doi.org/10.1186/1750-0680-5-8, 2010.

McGrath, M. J., Petrescu, A. M. R., Peylin, P., Andrew, R. M., Matthews, B., Dentener, F., Balkovič, J., Bastrikov, V., Becker, M., Broquet, G., Ciais, P., Fortems, A., Ganzenmüller, R., Grassi, G., Harris, I., Jones, M., Knauer, J., Kuhnert, M., Monteil, G., Munassar, S., Palmer, P. I., Peters, G. P., Qiu, C., Schelhaas, M.-J., Tarasova, O., Vizzarri, M., Winkler, K., Balsamo, G., Berchet, A., Briggs, P., Brockmann, P., Chevallier, F., Conchedda, G., Crippa, M., Dellaert, S., Denier van der Gon, H. A. C., Filipek, S., Friedlingstein, P., Fuchs, R., Gauss, M., Gerbig, C., Guizzardi, D., Günther, D., Houghton, R. A., Janssens-Maenhout, G., Lauerwald, R., Lerink, B., Luijkx, I. T., Moulas, G., Muntean, M., Nabuurs, G.-J., Paquirissamy, A., Perugini, L., Peters, W., Pilli, R., Pongratz, J., Regnier, P., Scholze, M., Serengil, Y., Smith, P., Solazzo, E., Thompson, R. L., Tubiello, F. N., Vesala, T., and Walther, S.: The consolidated European synthesis of CO2 emissions and removals for EU27 and UK: 1990–2020, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2022-412, in review, 2023.

Petrescu, Ana Maria Roxana, Glen P. Peters, Greet Janssens-Maenhout, Philippe Ciais, Francesco N. Tubiello, Giacomo Grassi, Gert-Jan Nabuurs, et al. 2020. "European Anthropogenic AFOLU Greenhouse Gas Emissions: A Review and Benchmark Data." Earth System Science Data 12 (2): 961–1001. https://doi.org/10.5194/essd-12-961-2020.

Petrescu, Ana Maria Roxana, Chunjing Qiu, Philippe Ciais, Rona L. Thompson, Philippe Peylin, Matthew J. McGrath, Efisio Solazzo, et al. 2021a. "The Consolidated European Synthesis of CH_4 and N_2O Emissions for the European Union and United Kingdom: 1990–

2017." Earth System Science Data 13 (5): 2307–62. https://doi.org/10.5194/essd-13-2307-2021

Petrescu, A. M. R., Qiu, C., McGrath, M. J., Peylin, P., Peters, G. P., Ciais, P., Thompson, R. L., Tsuruta, A., Brunner, D., Kuhnert, M., Matthews, B., Palmer, P. I., Tarasova, O., Regnier, P., Lauerwald, R., Bastviken, D., Höglund-Isaksson, L., Winiwarter, W., Etiope, G., Aalto, T., Balsamo, G., Bastrikov, V., Berchet, A., Brockmann, P., Ciotoli, G., Conchedda, G., Crippa, M., Dentener, F., Groot Zwaaftink, C. D., Guizzardi, D., Günther, D., Haussaire, J.-M., Houweling, S., Janssens-Maenhout, G., Kouyate, M., Leip, A., Leppänen, A., Lugato, E., Maisonnier, M., Manning, A. J., Markkanen, T., McNorton, J., Muntean, M., Oreggioni, G. D., Patra, P. K., Perugini, L., Pison, I., Raivonen, M. T., Saunois, M., Segers, A. J., Smith, P., Solazzo, E., Tian, H., Tubiello, F. N., Vesala, T., van der Werf, G. R., Wilson, C., and Zaehle, S.: The consolidated European synthesis of CH_4 and N_2O emissions for the European Union and United Kingdom: 1990–2019, Earth Syst. Sci. Data, 15, 1197–1268, https://doi.org/10.5194/essd-15-1197-2023, 2023.

UNFCCC: Kyoto Climte Change Decision, available at: https://unfccc.int/process-and-meetings/conferences/past-conferences/kyoto-climate-change-conference-december-1997/decisions-kyoto-climate-change-conference-december-1997, (last access: 5 October 2020), 1997.

VERIFY-CoCO2 Synthesis Plots: http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/, last access: 12 May 2023.

Vizzarri, M., Pilli, R., Korosuo, A., Blujdea, V. N. B., Rossi, S., Fiorese, G., Abad-Vinas, R., Colditz, R. R., and Grassi, G.: Setting the forest reference levels in the European Union: overview and challenges, Carbon Balance Manage, 16, 23, https://doi.org/10.1186/s13021-021-00185-4, 2021.

6 APPENDIX A: CH4 synthesis

Current view on CH_4 emissions from the EU27 and six top global emitters

or

The consolidated synthesis of CH_4 emissions in the EU27 and six top global emitters

or

The consolidated synthesis of global observation- and inventory- based methane emissions estimates: reconciliation and challenges

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

[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]Department of Climate, Air and Sustainability, TNO, Princetonlaan 6, 3584 CB Utrecht, the Netherlands
[8]Istituto Nazionale di Geofisica e Vulcanologia, Sezione Roma 2, via V. Murata 605, Roma, Italy
[9]Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria, Via Salaria km 29300, 00015 Monterotondo, Rome, Italy
[10]International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria
[11]Research Institute for Global Change, JAMSTEC, Yokohama 2360001, Japan
[12]Chiba University, 1-33 Yayoicho, Inage Ward, Chiba, 263-8522, Japan
[13]Department of Thematic Studies – Environmental Change, Linköping University, Sweden
[14]Laboratoire des Sciences du Climat et de l'Environnement, 91190 Gif-sur-Yvette, France
[15]Department of Physical Geography and Ecosystem Science, Lund University, SE-223 62 Lund, Sweden
[16]Food and Agriculture Organization of the United Nations, Statistics Division. 00153 Rome, Italy
[17]Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Thiverval-Grignon, France
[18]China
[19]Biogeochemistry and Modeling of the Earth System, Université Libre de Bruxelles, 1050 Bruxelles, Belgium
[20]Norwegian Institute for Air Research (NILU), Kjeller, Norway

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

1 Abstract

Knowledge of the spatial distribution of the fluxes of greenhouse gases and their temporal variability as well as flux attribution to natural and anthropogenic processes is essential to monitoring the progress in mitigating anthropogenic emissions under the Paris Agreement and to inform its Global Stocktake. This study provides a consolidated synthesis of CH_4 emissions using bottom-up (BU) and top-down (TD) approaches for the European Union (EU27) and six global major emitters and updates earlier syntheses (Petrescu et al., 2020, 2021, 2023). The work integrates updated emission inventory data, process-based model results, data-driven sector model results, inverse modelling estimates, and, whenever, available their uncertainties. Whenever possible, it extends the period up until 2021. BU and TD products are compared with European National GHG Inventories (NGHGI) reported by Parties under the United Nations Framework Convention on Climate Change (UNFCCC) in 2023. Results of six top global emitters are included. By comparing NGHGIs with other approaches, the activities included are a key source of bias between estimates e.g., anthropogenic and natural fluxes, which, in atmospheric inversions, are sensitive to the prior geospatial distribution of emissions. Over the studied period, which covers a sufficiently robust number of overlapping estimates, and most importantly the NGHGIs, the total **CH_4 emissions in EU27** show a steady decreasing trend compared to 1990, which is needed for the EU's climate reduction targets. For **global emitters**, reductions in CH_4 emissions are mostly seen for Annex I parties, while non-Annex I parties show increased emissions.

In the **EU27**, the anthropogenic BU approaches are directly comparable, accounting for mean emissions over 2015 to last available year of 18 Tg CH_4 yr^{-1} for EDGAR v7.0 (last year 2021), 16 Tg Tg CH_4 yr^{-1} for GAINS (last year 20202) and 19 Tg CH_4 yr^{-1} for FAOSTAT (last year 2020), similar to the NGHGI estimates of 15.6 ± 2 Tg CH_4 yr^{-1}. TD inversions estimates give higher emission estimates, as they also detect natural emissions. Over the same period, the median of high-resolution regional TD inversions report a mean emission of 20 Tg CH_4 yr^{-1}, while the median of six coarser-resolution global TD inversions result in emission estimates of 24 Tg CH_4 yr^{-1}.. The magnitude of natural emissions (peatland and mineral soils, natural rivers, lakes and reservoirs, geological and biomass burning) together account for 6.6 Tg CH_4 yr^{-1} and could represent the gap between NGHGI anthropogenic BU results and TD total inversions.

For the top **global emitters**, the situation strongly differs between Annex I and non-Annex I countries, Anthropogenic CH_4 estimates from UNFCCC BURs show large differences in non-Annex I countries compared to atmospheric-based estimates. It poses an important reservation on the status of the global CH_4 pledge and future implementation of Global Stocktake initiative, not only from the availability of data, but also from its quality point of view.

By comparing TD and BU methods defined in this study, we hope to steadily engage more parties in using atmospheric methods in complementing their UNFCCC inventories. New steps involving analysis at finer temporal resolutions and estimation of emissions over intra-annual timescales, of great importance for CH_4, may help identify sector contributions to divergence between prior and posterior estimates at the annual/inter-annual scale. Even if currently comparison between CH_4 inversions estimates and NGHGIs is uncertain because of the spread in the inversion results, TD inversions inferred from atmospheric observations represent the most independent data against which inventory totals can be compared. With anticipated improvements in atmospheric modelling and observations, as well as modelling of natural fluxes, TD inversions may arguably emerge as the most powerful tool for verifying emissions inventories for CH_4, and other GHGs. The referenced datasets related to figures are visualized at https://doi.org/10.5281/zenodo.7553800 (Petrescu et al., 2023).

2 Introduction

The latest data from the NOAA Global Monitoring Laboratory (GML) network reported in 2021 the highest value of CH_4 atmospheric concentration to record, accounting for 17 parts per billion (ppb), reaching 1895.7 ppb, the largest annual increase recorded since systematic measurements began in 1983, and 162 % greater than pre-industrial levels. From NOAA's observations, scientists estimate global methane emissions in 2021 are 15% higher than the 1984-2006 period (https://gml.noaa.gov/ccgg/trends_ch4/).

As of today, "control of many methane sources, mainly of anthropogenic nature, is technically possible", researchers from NOAA say. The natural sources dominated by wetlands represent an anomaly observed during the last decade, mostly observed in the Northern hemisphere and Peng et al., 2022 found that most wetlands of the world are lately exposed to increased temperatures and precipitation rates and a similar, abnormally large, growth rate of 14.8 ppb yr^{-1} was also detected from total column concentration measurements (XCH_4) by the Greenhouse Gases Observing Satellite (GOSAT). In 2020, warmer and wetter wetlands over the Northern Hemisphere increased emissions by 6.0 ± 2.5 Tg CH_4 yr^{-1} relative to 2019 and dominated the net increase in global wetland emissions (6.0 ± 2.3 Tg CH_4 yr^{-1}) in 2020 (Peng et al., 2022).

Methane in the atmosphere is generated by many different sources, of both natural and anthropogenic origin. The natural sources of CH_4 are dominated by peatlands (e.g. wetlands), while anthropogenic emissions come from agricultural activities (livestock and rice farming), waste management (landfills and water treatment plants) and the production, transportation, and use of fossil fuels. Determining which specific sources are responsible for variations in annual increases of methane is complex, but scientists estimate that fossil fuel production and use contributes roughly 30% of the total methane emissions. These industrial sources of methane are relatively simple to pinpoint and control using current technology (NOAA news release, https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021).

The global contribution of CH_4 to the global radiative forcing has been estimated by the IPCC AR6 (IPCC, 2021) report to be of about 0.5º C of present global warming over the period 1850–1900 (Stavert et al., 2022). Methane has a relatively short perturbation lifetime (12.4 years (Balcombe et al., 2018)) and high global warming potential times that of CO_2 over a 100-year period (IPCC, 2021)). As such, a decline in CH_4 emissions will rapidly reduce global CH_4 concentrations and mitigate the impact of climate change at decadal time scales (United Nations Environment Programme & Climate & Clean Air Coalition, 2021). However, any efforts to target CH_4 emissions reductions 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. To independently assess the progress of EU27 countries towards their targets (cut its emissions by at least 55% by 2030 and the Green Deal to reach zero net emissions of greenhouse gases in 2050), the European Commissions (EC) indicated that an objective way to monitor anthropogenic CO_2 emissions and their evolution over time was needed. Such a capability would provide consistent and reliable information to support informed political and decision-making processes. The European Commission is therefore establishing an operational observation-based anthropogenic CO_2 emissions monitoring and verification support capacity (**CO_2MVS**) as part of its Copernicus Earth Observation programme. As part of the CO_2MVS concept, which combines information from different observational datasets and from existing knowledge about emissions together with detailed computer models of the Earth system, observations can also provide information about the processes that are responsible for the exchange of CH_4 between the Earth's surface and the atmosphere such as human activities (i.e., CH_4 leaks from the oil and gas production areas). The signal of anthropogenic emissions in the variables is weak compared to those from natural sources, therefore, advanced data assimilation methods (refs.) can then make adjustments to emissions that are consistent with information from observations and constrained by the physical knowledge encapsulated in the models.

Next to commitments adopted by the EC, at COP26 was launched the Global CH_4 Pledge (GMP) initiative. Its goal of cutting anthropogenic CH_4 emissions by at least 30 % by 2030 from 2020 levels 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 energy security, food security, health, and development gains. About 150 countries joined this pledge and about fifty already developed national CH_4 action plans or are in the process of doing so (https://www.state.gov/global-methane-pledge-from-moment-to-momentum/). As Agriculture and Waste are the main anthropogenic sources for CH_4 emissions, at COP27 a GMP Food and Agriculture and Waste pathways were launched, foreseeing actions that increase agricultural productivity, reduce food loss and waste by supporting small farmers and increase innovation.

Following the global context introduced above, this paper updates the recently published European synthesis Petrescu et al., 2023 and deepens analysis on sources of anthropogenic and natural CH_4 emissions in the EU27 and six top global emitters. It examines both Annex I and non-Annex I estimates from observation-based bottom-up process-based models and inversions-based top-down approaches (satellite observations) by identifying and explaining differences with official inventory reports submitted by parties to the UNFCCC. In depth attention is given to methodological issues identified in the DSS (D8.4 $CoCO_2$ report) and previous studies (e.g., Petrescu et al., 2020, 2021, 2023) when comparisons are performed between approaches. The criteria for choosing the six countries were mainly based on location and the importance / magnitude of natural emissions which might help explain differences with TD products. By using multiple methodologies, uncertainties can be estimated by looking at the range in both emissions and trends. This will also allow strengthening the robustness of such comparison exercises when using independent atmospheric observations in estimating trends and patterns for regional/national CH_4 emissions.

3 Methods and data

3.1 Verification practices in official UNFCCC NGHGIs

In the context of NGHGIs, the good practice quality assurance/quality control (QA/QC) ensure quality of the inventory. Verification refers specifically to those 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 are truly independent (Andrew 2020) as they may rely on, for example, the same energy data reported by a country. Experience has shown that performing detailed comparisons (Petrescu et al., 2021, 2023) 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 require observations of atmospheric concentrations or fluxes, that are then coupled to a transport model. These methods are more complex, uncertain, and computationally expensive, but are also more independent than inventory-based comparisons (although inversions do need prior input on inventories). In both cases, correspondence between the national inventory and independent estimates increases the confidence and reliability of the inventory estimates by confirming the results. Since most developed countries have reported UNFCCC inventories for decades and these have been continually refined, most focus is on observation-based estimates. As an increasing number of developing countries begin more detailed and frequent reporting, comparisons with independent emission inventories will initially be an important method of verification for those countries.

In the 2019 refinement of the IPCC guidelines, the guidance on the use of atmospheric measurements for verification was extended (IPCC 2019). The refined guidelines highlight that notable advances that have been achieved in the application of inverse models of atmospheric transport for estimating emissions at national scale. Consequently, there are several countries that now use atmospheric measurements for verification of parts of their inventories. Australia and New Zealand have estimated regional CH_4 emissions to help better understand the methods and their potential. Germany performs various cross validation checks with available data, some of which is based on observations. The UK and Switzerland, however, have developed more comprehensive methods based on inversion modelling, covering almost all GHGs in addition to CH_4. Building on modelling experience, the country reporting confirms that most potential lies in using observations to verify fluorinated gases, the uncertainty in CH_4 gives potential for verification but requires more comprehensive inversion modelling.

It is important to understand why there are different challenges, and thereby opportunities, using observation-based emission estimates. These challenges and opportunities apply for CH_4 and even though inversions currently have high uncertainty, verification of CH_4 emissions is still possible since the inventories are sufficiently uncertain. In geographic areas with sufficiently strong ground-based observation networks, the inversions will have more value. In some cases, natural emissions and seasonality can be additional challenges.

3.2 Anthropogenic CH_4 emissions from the NGHGIs

In EU27, Member States (MS) report yearly their GHG emissions to the UNFCCC in the so-called Common Reporting Format (CRFs) tables and National Inventory Reports (NIRs). Here, anthropogenic CH_4 emissions from the five UNFCCC sectors (incl. LULUCF) were grouped together. Also, for the other Annex-I parties (Russia and USA), the sum of the CH_4 fluxes reported in their CRF tables submitted in 2022 were used.

Regarding CH_4 emissions from wetlands, following the recommendations of the 2013 IPCC Wetlands supplement (IPCC, 2014) only emissions from managed wetlands are reported by Parties. According to NGHGI data, between 2008 and 2021, managed wetlands in the EU27 for which emissions were reported under the LULUCF (CRF table 4(II) accessible for each EU27 country[2]) represent one fourth of the total wetland area in EU27 (G. Grassi, EC-JRC, pers. comm.) and their emissions summed up in 2021 to 0.1 Tg CH_4 yr^{-1}. The NGHGIs do not include any lateral fluxes from inland waters but do include biomass burning emissions reported under the LULUCF sector.

The presented uncertainties in the emission levels of the individual countries and the EU27 bloc were calculated by using the methods and data used to compile the official GHG emission uncertainties that are reported by the EU under the UNFCCC (NIRs, 2022). 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, under Article 7(1)(p) of Regulation (EU) 525/2013. For detailed regarding gap-filling harmonization procedure please see Appendix A1, Petrescu et al., 2023.

Non-Annex I countries report their emissions to the UNFCCC in the so-called Biannual Reports (BRs) and their updates (BURs) for. In this study, Brazil, China, Indonesia and the Democratic Republic of Congo (DR Congo) were investigated.

For *Brazil*, information from its fourth biennial update report (4th BUR) (Brazil, 2020) that give both total and sectoral split emission values for years 1994, 2000, 2010, 2012, 2015 and 2016, were used.

2 https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019

For *China*, information from its second biennial update report (2nd BUR) Tables 2-10, 2-13, 2-14, 2-15, and 2-16 (China, 2019) were used. 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 biennial update report (3rd BUR) in 2021 (Indonesia, 2021). IDN total CH_4 emissions time series per sector as reported by the 2nd UNFCCC BUR (2001-2016) and revised 3rd BUR (2000 and 2019, Table 2). For 2017 and 2018 only Agriculture CH4 emission were detailed by the 3rd BUR. Data uncertainty for 2019 activity and EFs are the same as reported in the BUR 2. The result of the uncertainty analysis showed that the overall uncertainty of the Indonesia's National GHG inventory with AFOLU (including peat fire) for 2000 and 2019 were approximately 20.0% and 19.9% respectively. A higher level of uncertainty, 10.4% for 2000 and 13.8% for 2019, occurred when the FOLU was excluded from the analysis.

The *DR Congo* submitted its first BUR in 2022. However, we only used total values reported for 2000-2018 (Table 12) (DR Congo, 2022).

3.3 Other CH_4 data sources and estimation approaches

The CH_4 emissions in the EU27 and non-Annex I countries belong to TD 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 as summarized in Table 1. The data (Table S1, Supplement) span the period from 1990 to 2021, with some of the data only available for shorter time periods or up until 2021. 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 1990-2021). Data sources are summarized in Table S1, with the detailed description of all products provided in SI.

Table 1: *Sectors included in this study and data sources providing estimates for these sectors. CAMS stands for Copernicus Atmosphere Monitoring Service.*

Anthropogenic (BU)[3] CH_4	Natural (BU)[4] CH_4	Regional TD CH_4	Global TD CH_4
1. Energy (UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT	Wetlands **EU27**: JSBACH-HIMMELI **Global**: LPJ-GUESS and CEOS (Worden et al., 2019) Peatlands, mineral soils: **EU27**: JSBACH-HIMMELI **Global**: LPJ-GUESS (wetlands)	**No sectoral split – total emissions** FLEXkF_v2023 VERIFY Community Inversion Framework (CIF): FLEXPARTv10.4 (NILU)	**No sectoral split – total emissions** MIROC4-ACTM (control) CAMS v21r (NOAA and NOAA_GOSAT runs) TROPOMI CTE-CH_4 (GCP2021) MIROC-ACTM (OH varying) **Sectoral split:** TROPOMI
2. Industrial Products and Products in Use (IPPU) (UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT			
3. Agriculture* (UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0, FAOSTAT			

[3] 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).

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

4. LULUCF total emissions (UNFCCC NGHGI (CRFs and BURs) and FAOSTAT 5. Waste (UNFCCC NGHGI (CRFs and BURs), GAINS, EDGAR v7.0)	Inland waters fluxes **EU27**: lakes, rivers and reservoirs ULB **Global:** lakes and reservoirs ORNL DAAC Geological fluxes Etiope et al., 2019 with updated activity Biomass burning (GFEDv4.1s)		$CTE-CH_4$ (GCP2021) MIROC-ACTM (OH varying) CEOS (GOSAT) Worden et al., 2019

The units used in this paper are metric tons (t) [1kt = 10^9 g; 1Mt = 10^{12}g] of CH_4. The referenced data used for the figures' replicability purposes are available for download at https://doi.org/10.5281/zenodo.7553800 (Petrescu et al., 2023). Upon request, the codes necessary to plot the figures in the same style and layout can be provided. The focus is on the EU27 and six top global emitters. In the VERIFY project and consequently used by the $CoCO_2$ project, a web tool was developed which allows for the selection and display of all plots for countries and groups of countries in Europe alone as well as major players overseas (see Table A1, Appendix A in Petrescu et al., 2023). The data, located on the VERIFY project website: http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/, is free and can be accessed upon registration.

3.4 Comparability issues between datasets

In the figures presented in this study, various inversions and inventory methods are plotted on the same figure, to allow a visual comparison. To allow for a valid comparison, a full uncertainty analysis, that would for example, quantify if one dataset has a statistically significant difference to another, given reported uncertainties, is needed. Very few datasets provide uncertainty information. Methods to present the results, including uncertainties, need to be improved. Next to this, to allow a valid comparison between the various inversions, also the partitions (anthropogenic, natural) should be compared correctly. However, this is difficult because not all report the same sectoral splits (see Table 2).

System boundary issues

When comparing datasets, a variety of system boundary issues arise (Andrew 2020; Grassi et al. 2018). Additional issues arise when comparing results from inversion products. Key issues are mentioned here:

Country borders/gridding

Transforming a gridded dataset into country totals requires dealing with grid cells that overlap country boundaries. A general system boundary issue is masking of gridded results to the country level, where it is important to know how modelling groups have defined emissions in each grid cell and to ensure the mask correctly captures country and economic zone effects, in line with how official NGHGIs are reported. Despite this potential system boundary issue, it is unclear whether it is important yet. Inversions currently relying on in-situ observations would not be affected by this, as the observations would not detect the emissions emitted at cruising altitude. For this reason, the TNO emission inventories include landing and take-off of all flights, domestic and international, but not the emissions at cruising altitude.

Land definitions

In a NGHGI context, the emissions are reported based on a 'managed land proxy'. This proxy was originally intended to represent anthropogenic activities and is defined to cover land "where human interventions and practices have been applied to perform production, ecological or social functions" (IPCC, 2006). Countries do not report emissions from spatial grids of their managed land definitions, but "intact" and "non-intact" has been found to be a good proxy for unmanaged and managed land (Grassi et al., 2021). In line with Bergamaschi et al. (2018) and Petrescu et al., 2021a and 2023, the potential significant contribution from natural unmanaged CH_4 sources (peatlands/wetlands, geological and inland water) is highlighted. Subtracting these unmanaged natural emissions from inversions is one way to approximate the system boundary of CH_4 emissions in NGHGIs.

Lateral fluxes

Carbon can cross national borders in a variety of methods, not all of which are well captured in models. Key processes include river transport and trade in agriculture commodities.

Temporal and spatial resolution

The temporal and spatial resolution is an area that is not clearly resolved. Inversion models can produce estimates at a potentially fine grid scale (kilometers) and fine temporal detail (hours), but this is far too resolved for most user applications. As a starting point, a region (e.g., city or region within a country) would be interested in annual emissions, but the availability of more detail could be tempting. At one level, the fine spatial and temporal detail may help identify and manage 'events' (acute pipeline leak). Since spatial resolution may help identify individual facilities, such as a powerplant or industrial site, which may help inventory agencies verify emissions from these facilities when they have facility level data. The fine spatial resolution allows aggregation to city- or region-level, matching as close as possible to jurisdiction boundaries. However, challenges may arise in mapping system boundaries: the results of an inversion can easily be aggregated to an arbitrary region, but data limitations may make it difficult for inventory-based approaches to provide estimates with a consistent system boundary, with transport emissions being one good example.

Trends and variability

Many emission estimates are reported at the annual level, and inventory-based approaches often do not consider variability. Further, the Paris Agreement is set around five yearly global Stocktakes, which indicates a desire to average trends over different time periods to remove interannual variability, from both weather and socioeconomic events. Inversion models, on the other hand, naturally include interannual variability. It is likely that inversion-based methods will need to somehow remove the variability, such as via averaging over periods (e.g., 5-year or 10-year) or by looking at trends. However, there are many ways that these comparisons could be made. There is the additional issue of identifying if a difference between two independent datasets is statistically significant. There is a clear need to better develop methods to deal with variability and statistical significance. There is also a need to estimate uncertainties in trends, not just the aggregate values, which is far more challenging as it requires understanding the correlations over time. With a user perspective in mind, there is a need to map to the policy needs, which may value trends over levels and may want to ignore variability. The methods used to compare aggregated emissions and trends, and how to deal with temporal and spatial resolution, will be important for the design and usefulness of future operational satellite missions.

Priors

The prior emission estimates are an important input and the specific inversion systems. When combined with observation data, the inversion system produces a new posterior estimate of emissions, which can then be compared back to the prior estimate, preferably incorporating a full uncertainty analysis. It is this comparison that is the core objective of inversions systems, therefore, it is critical that the prior data is of high quality and robust.

The UNFCCC NGHGI data is rarely used as a prior, as it 1) rarely has the necessary spatial and temporal resolution, and 2) the data does not have global coverage. Other data sets are often used, such as EDGAR. Further, quite often older datasets are used as they have the preferred resolution: EDGAR version 4.3.2, up to 2012, is often used because of its spatial and temporal resolution, and global coverage, with various extrapolation schemes used to extend the data to the most recent years. However, the prior emissions can often differ substantially from the national GHG inventories. It is hard to determine the importance of the prior estimate on the posterior estimate and the resulting uncertainties. In many countries, prior estimates can already differ from UNFCCC estimates by up to a factor of ten (e.g., CH_4 in the Nordic countries). Key reasons for differences are often the fact that global datasets (e.g., EDGAR) do not use country specific emission factors or activity data. While there are many initiatives to produce datasets of high spatial and temporal resolution (e.g., in $CoCO_2$), often national inventory agencies do not have sufficient resources or mandate to provide spatially or temporally resolved datasets.

A further challenge is the uncertainty data on prior estimates. While some datasets provide uncertainties (e.g., UNFCCC and EDGAR for a single year), these uncertainties often only capture parametric uncertainties and not structural uncertainties. For example, the aforementioned biases in EDGAR estimates for the Nordic countries do not have uncertainties that capture the UNFCCC estimates.

There is a need to improve the prior estimates used as input into inversion systems. This really has three components: 1) ensuring the availability of updated emissions data at an appropriate level of sector, temporal, and spatial detail, 2) ensuring inversions systems assimilate the latest data estimates from verified sources, and 3) ensuring that prior estimates have fully characterized uncertainties.

Aggregation

Inversions are affected by the size of the country, location (latitude, longitude), geography, albedo, number of observations, types of observations, and so on. An experienced modeller may implicitly (and even subconsciously) weigh this information when analysing results from a given country but would not mention this information explicitly as it is common knowledge within the inversion community (National Academies of Sciences, Engineering, and Medicine 2022). This makes it hard for a user to understand the implicit weights put into different comparisons. There are, potentially, some methods to alleviate some of these issues, such as through maps which show the uncertainty across geographic regions, and how they change with given factors (such as new observations, VERIFY D6.13). Because of some of these issues, modellers often aggregate regions together as there is more confidence in the aggregated results. The reasons for some groupings and the optimal size of regions as an element analysis are often unclear and unstated.

Further, many countries border with other countries, requiring a method to aggregate the grid level inversion data to a country. Particularly for inversion models with a coarser grid, aggregation of the grid cells will not necessarily be a perfect match to country boundary. This problem becomes smaller with bigger regions, or regions with long coastlines, and is one reason that VERIFY aggregated many smaller countries together to bigger regions.

Statistical significance - Uncertainties

One method that modellers use to determine if an inversion gives an improvement over the prior emission estimate is to assess a reduction in the uncertainty. The prior emissions used as input into an inversion model should have uncertainties, and a full inversion analysis will include uncertainties on the posterior estimate, with the reduction in uncertainty between the two estimates of particular interest. In a well constrained inversion, the uncertainty of the posterior emissions should decline, and the posterior emissions should converge to the ‘true’ value. If the difference between the prior and posterior estimate is statistically significant, then this would suggest that the inversion has identified an incorrect prior emission estimate. The inventory-based emission estimate will additionally have uncertainties, though some argue these are not sufficiently robust for verification purposes (National Academies of Sciences, Engineering, and Medicine 2022). It is not generally clear how inventory uncertainties can be compared to inversion uncertainties, as the methods to produce the uncertainties differ.

Methods to reveal statistically significant levels or trends need to be developed. There are often offsets in inversion models, because of inconsistencies in observations, which may make trends more robust. In a policy context, the uncertainty on the emission trend may be more important, but also this is harder to estimate as it requires knowledge of correlations in emission estimates over time.

Model ensembles

Research projects, such as VERIFY, often focus on multiple model analysis (ensembles). The UNFCCC emission inventory would be compared against, for example, 13 land surface models and 22 inversion models (Saunois et al., 2020). From a scientific perspective, the model ensemble is often considered a more robust estimate of the mean and uncertainty, as inherent model biases can be captured. From an inventory perspective, individual model comparisons may be more productive, as various input variables or processes can be compared directly to the inventory. Doing this for each model becomes time consuming. The CO$_2$MVS system is currently envisaged to be one global modelling and data assimilation system based on ECMWF’s Integrated Forecasting System (IFS).

Understanding the implications of these different choices, and how to capture structural uncertainties across models and methodologies, will be a challenge for a single IFS that needs to be resolved. Currently, most inventory comparisons in UNFCCC National Inventory Reports (UK, Switzerland) use single model comparisons.

Anthropogenic and natural fluxes

Most emission inventories aim at estimating anthropogenic emissions, while most inversion models see both anthropogenic and natural emissions. Thus, methods are needed to separate the anthropogenic flux from the total flux (Deng et al. 2022). This is a particularly important issue for CH_4 where globally natural emissions are of similar magnitude as anthropogenic emissions, with bigger variations at the regional level. Further, climate change may mean natural emissions change in ways that models can’t yet resolve, for example, a warmer climate may increase natural emissions of CH_4.

Standardization

Inverse analysis systems are not yet standardized; therefore, there is room for additional progress and refinement of emission estimates and uncertainties derived from atmospheric observation and inverse models. The Community Inversion Framework (CIF, Berchet et al., 2021) is a move in this direction. However, improvements are still needed to ensure common formatting and presentation of the results, in addition to the use of common language and terminology, as discussed earlier.

4 Results

4.1 NGHGI official reported inventory estimates

EU27

Figure 1 presents anthropogenic CH_4 emissions reported to the UNFCCC in 2022 from the NGHGI CRFs (EU27, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019) and Indonesia (3rd in 2021). For EU27, in 2022 the total CH_4 emissions account for 15 Tg CH_4 yr^{-1} and represent 10.5 % of the total EU27 emissions (in CO_2e, GWP 100 years, IPCC AR4[5]). CH_4 emissions are predominantly related to agriculture (Figure 1, yellow) and in 2020 account for 8.2 Tg CH_4 yr^{-1} ± 0.8 Tg CH_4 yr^{-1}) or 54 % of the total EU27 CH_4 emissions. Anthropogenic NGHGI CH_4 emissions from the LULUCF sector are very small for EU27 e.g., 0.26 Tg CH_4 yr^{-1} or 1.7 % in 2020, including emissions from biomass burning. The data from Figure 1 shows steady decreasing trends with respect to the 1990 CH_4 levels. The reduction in total CH_4 emissions in 2020 with respect to 1990 is of 8.4 Tg CH_4 (35.7 %) at an average yearly rate of -1%.

USA

Despite the stabilization of the USA NGHGI CH_4 data trend since 2013, the overall trend shows an overall decrease in total CH_4 emissions (Fig. 1 black dotted line) with an overall reported reduction of 15 % in 2020 with respect to 1990, corresponding to 4.7 Tg CH_4, with Energy and Waste having the highest reduction shares (27% and 34% respectively) while Agriculture and LULUCF registered a 17% and 40% increase in emissions.

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

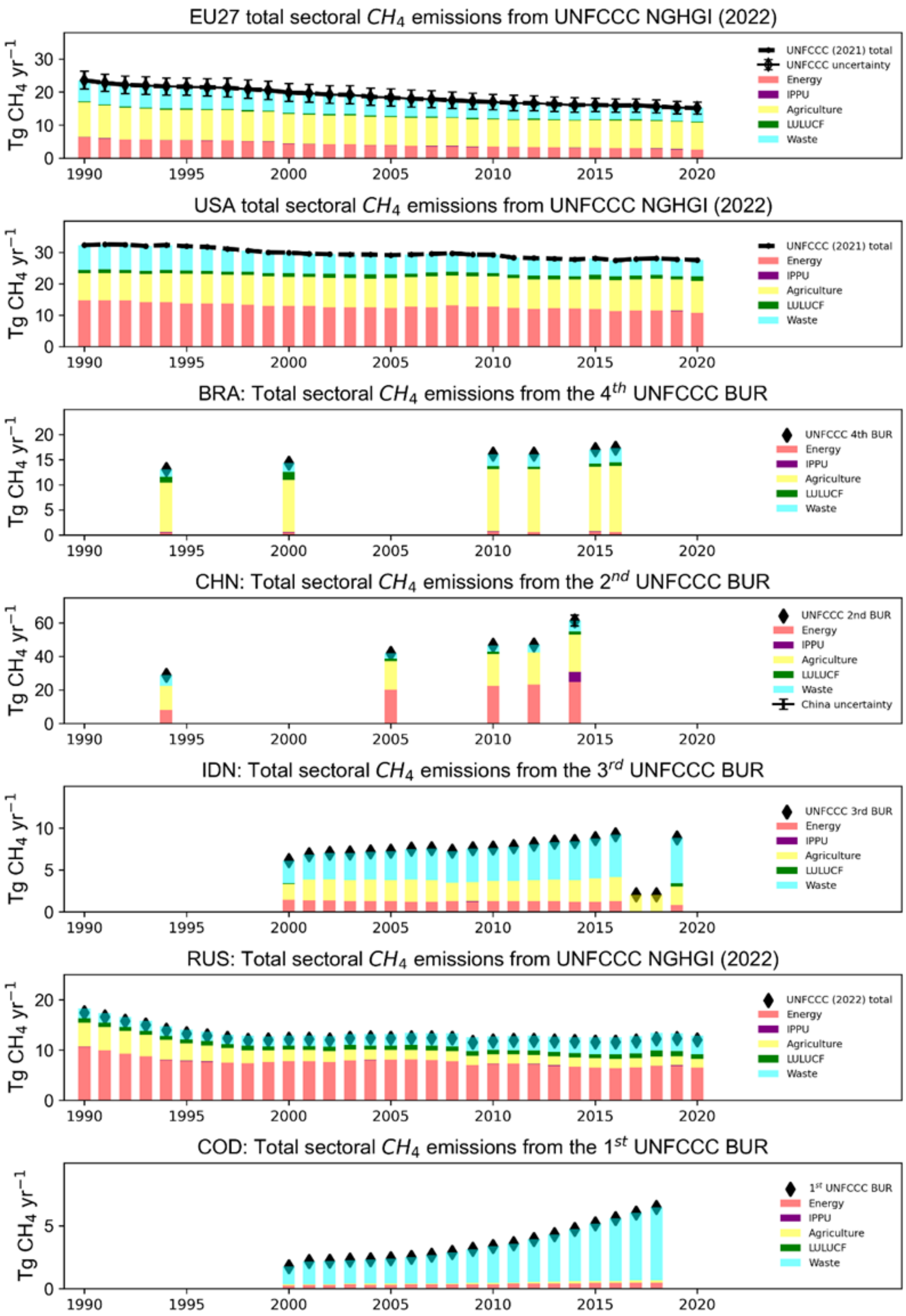

Figure 1: Total anthropogenic CH_4 emissions (excl. LULUCF) from bottom-up (BU) inventories as: UNFCCC NGHGI CRFs (EU27, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021) and DR Congo (1st in 2022) and three other global datasets: EDGARv7.0, GAINS (no IPPU) and FAOSTAT. The relative error on the UNFCCC value represents the NGHGI (2021) 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.

Brazil

In 2021 Brazil submitted its 4th BUR. The observed trend in total CH_4 emissions is increasing, registering 32.5 % more emissions in 2016 compared to 1994, with major contribution from the agricultural sector (76 %). After agriculture, the CH_4 emissions from the Waste sector are the second contributor, with 16 %.

China

China's CH_4 emissions contribute to climate change more than the amount emitted by many developed countries combined. The rapid growth of China's coal demand has important implications for CH_4 emissions from coal mining or coal mine methane (CMM) emissions (https://www.sciencedirect.com/science/article/abs/pii/S0048969720318088).

The second Chinese UNFCCC BUR CH_4 data shows increasing trends in total CH_4 emissions with an increase reported in 2014 of 112 % compared to 1994, corresponding to 32 Tg CH_4, with Energy and Agriculture sectors increasing their emissions with 214 % and 54 % in 2014 compared to 1994.

Indonesia

The IDN 3rd BUR data (2000 and 2019) shows increasing trends in total CH_4 emissions. The time series 2001-2006 belongs to the 2nd BUR submitted in 2018. In 2019 the reported increment is 44 % higher than in 2000, corresponding to 2.6 Tg CH_4. The yearly increment is on average 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. CH_4 emissions from the other sectors remain equal.

Russia

The trend in total and sectoral NGHGI CH_4 emissions in Russia is decreasing, with 31 % less emissions reported in 2020 compared to 1990. The sectors contributing the most to this decrease are Agriculture (62 % less emissions) and Energy (40 %). The waste sector shows a slight increase in emissions (5 %).

DR Congo

For its first BUR, DR Congo submitted emissions from Energy, Agriculture and Waste for 2000-2018. With respect to 2000, in 2018 the Congo emissions increased six times more and the majority of emissions in DR Congo belong to Waste, 90 % of the total emissions.

4.2 NGHGIs compared to other bottom-up estimates

Figure 2 shows UNFCCC (CRFs and BUR) estimates from EU27 and six global countries compared to global bottom-up data sets.

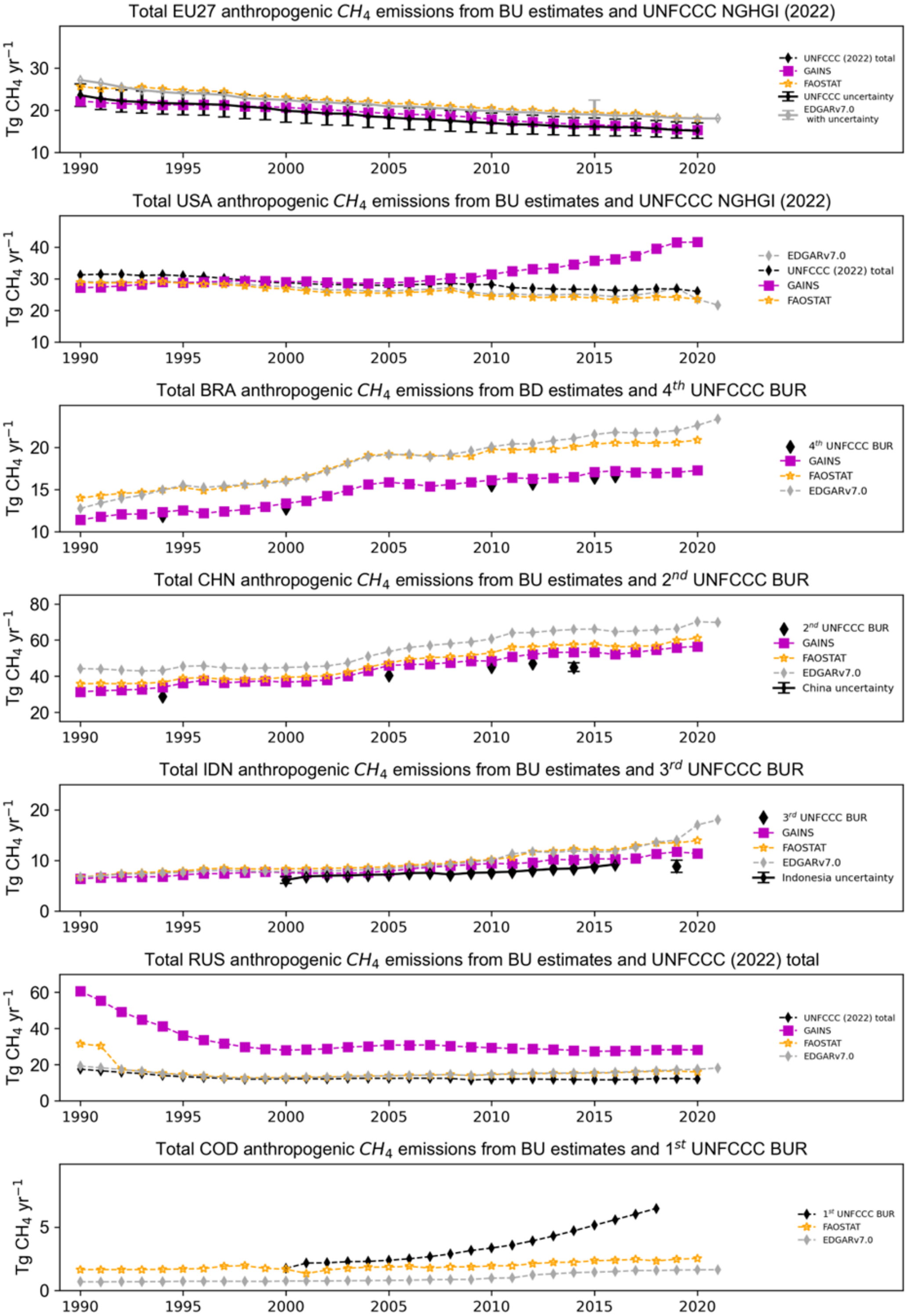

Figure 2: ***Total anthropogenic CH_4 emissions (excl. LULUCF) from bottom-up (BU) inventories as: UNFCCC NGHGI CRFs (EU27, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021) and DR Congo (1st in 2022) and three other global datasets: EDGARv7.0, GAINS (no IPPU) and FAOSTAT. The relative error on the UNFCCC value represents the NGHGI (2021) reported uncertainties computed with the error propagation method (95% confidence interval) and gap-filled to provide respective estimates for each year.***

The EDGARv7.0 uncertainty in 2015 was calculated as described in Solazzo et al., 2021. China and Indonesia report uncertainties, for 2014 and 2000 and 2019 respectively (BUR). Total COD UNFCCC BUR emissions do not include IPPU.

From Figure 2, it is notable that, except for the EU27 and USA which show decreasing trends in emissions from all data sets (USA except for GAINS), all the other countries show increasing trends. The match between UNFCCC reported emissions and all the data sources is satisfactory, with few exceptions as following:

- For *EU27*, the differences between the UNFCC NGHGI average for 1990-2020 and the other three data sets is less than 5 %.
- For the *USA*, GAINS reports high emissions after 2010. This is due to the Energy sector and the use of emission factors 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, as illustrated in the Supplementary Figure S6-1 (Höglund-Isaksson et al., 2020). For the US, total gas production increased by 47% between 2006 and 2017. Recent revisions for the agriculture livestock emissions concern updates of activity data and reported emission factors to latest statistics (FAOSTAT, 2018; UNFCCC, 2016; 2018) and a review of available technical abatement options for CH_4. A further difference might also be due to the large-scale extensive dairy and cattle farming in some parts of the USA, with animals typically grazing outdoor or staying outdoors in feedlots. In GAINS, there are no CH_4 mitigation options considered to control manure management emissions from such systems, however, there is assumed to be a potential to reduce enteric fermentation emissions by 10% through breeding and by maximum 30% if breeding is combined with interseeding of natural pastures with grass legumes, adding fodder crops and grass legume mixtures.
- For *Brazil*, UNFCCC and GAINS report similar emissions. The EDGARv7.0 and FAOSTAT report around 23 % more emissions for the averaged 1990-2021 but with similar trends. This is explained by the same AD and EF used to calculate emissions as since 2022, FAOSTAT includes estimates for all IPCC economic sectors: Energy, IPPU, Waste and Other. These data are sourced from the PRIMAP-hist v2.4 dataset (Gütschow et al., 2021). Emissions totals from agrifood domain are computed following the Tier 1 methods of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National greenhouse gas (GHG) Inventories. Emissions from other economic sectors as defined by the IPCC are also disseminated in the domain for completeness. Emissions are calculated based on data from the UN Statistical Division (UNSD), the International Energy Agency (IEA) and other third parties.
- Surprisingly, also for *China*, the bottom-up anthropogenic estimates agree with the BUR reported data, with EDGARv7.0 showing the highest estimates. According to GAINS, the primary drivers for growth in CH_4 Chinese emissions are due to a mix of sources, mainly increased coal mining.
- In *Indonesia* the three global datasets agree well up until 2010, while after all there report an increase in emissions compared to the UNFCCC BUR emissions.
- For *Russia*, GAINS emissions are much higher than NGHGIs and the other two data sets. The trend is set by emissions from the Energy sector, which for Russia, assumptions on the average composition of the associated gas generated from oil production have been revised based on information provided in Huang et al. (2015). The higher emissions might be caused by increased flaring. GAINSv4 estimates a decline in global CH_4 emissions in the first half of the 1990s, primarily a consequence of the collapse 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). Initial use of old statistics belonging to former USSR might also have caused the differences with other datasets between 1990-1998.

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4.3 NGHGIs compared to top-down atmospheric-based CH_4 estimates

Chandra et al., 2021 identifies globally, two sources which triggered increases and decreases of CH_4 emissions in different countries. The first is the global emission increase due to global fugitive coal emissions which could explain approximately 80 % of the emission increase estimated for e.g. China (21.5 Tg yr^{-1}) during 2000 – 2015. The emission decrease from fugitive emissions from the oil and gas industry helped to stabilize CH_4 concentration in the 1990s and then contributed to the renewed CH_4 growth since the late 2000s.

The other major sector source that drove changes in the CH_4 growth rate arises from an increase in emissions from enteric fermentation and manure management. The increase in emissions from enteric fermentation and manure management is caused by the greater intensity of ruminant farming as estimated by the FAO and the emission inventories (Crippa et al. 2020; Wolf et al. 2017; FAOSTAT 2018). The inventory emissions from waste treatments can account for up to 43 % of the linear increase in emissions for the rest of the world. The trends in other anthropogenic emissions are balanced by the natural emission changes globally or by the changes in CH_4 loss due to the reaction with OH in the troposphere.

Figure 3 presents the TD versus UNFCCC official reported emissions for EU27 and the six global emitters.

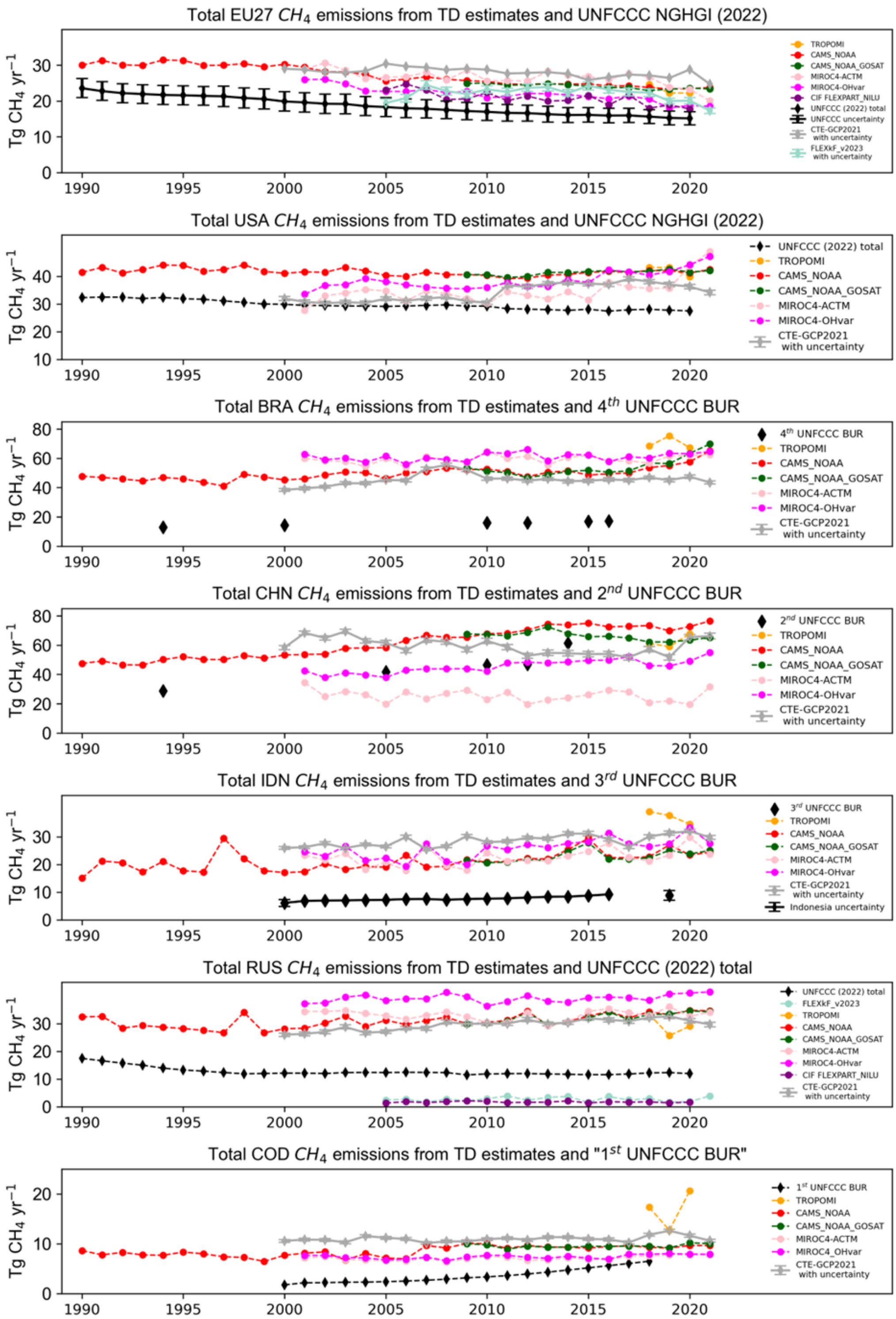

Figure 3: ***Total CH_4 emissions (incl. LULUCF) from UNFCCC NGHGI (2022) CRFs (EU27, USA and Russia) and BURs (Brazil (4th in 2021), China (2nd in 2019), Indonesia (3rd in 2021) and DR Congo (1st in 2022) and top-down inversions as following: for EU27 both regional (FLEXkF_v2023 and VERIFY CIF FLEXPART_NILU) and global (TROPOMI, CAMS_NOAA, CAMS_NOAA_GOSAT, CTE_GCP2021 and MIROC4-ACTM control and OH varying runs) products. The relative error on the UNFCCC value represents the NGHGI (2021) 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 for 2000 and 2019 (13.8 %). Total COD UNFCCC BUR emissions do not include IPPU.

For the ***EU27***, inversions place total CH_4 emissions in the range of 25-35 Tg CH_4 yr^{-1}, in line with previous estimates published in Petrescu et al., 2021 and 2023. As this is the total flux, and UNFCCC NGHGI report only managed anthropogenic emissions, the gap should be filled by the natural emissions. There is good agreement in trends, inversions showing a higher variability due to specific priors (see table 2) which give a strong seasonal signal (e.g., wetlands).

In the ***USA***, the trends observed in all TD products are slightly increasing, despite a slow decreasing trend seen in inventories and these could be influenced by the recent observed increase in natural emissions (Nisbet et al., 2023).

For ***Brazil***, TROPOMI reports less CH_4 emissions for 2020 due to less emissions from biomass burning seen in the partitions. The major emissions belong to wetlands, followed by anthropogenic emissions apart from rice. To note that TROPOMI results for 2018 are only available for May-December,

In ***China***, all TD estimates are higher than the UNFCCC BUR values, except for MIROC-ACTM OH varying run (OH iav: Patra et al., JGR, 2021) which is in line with the BURs. The MIROC-ACTM control run shows the lowest estimates. The use of OH iav helps to better estimate the regional CH_4 emissions, at least for the trends. The exact reasons are yet to be explored. For some months, MIROC-ACTM reports negative emissions in the East Asia region. One reason for this might be the fact that inversions are still ill-constrained by observations (only 60 sites globally) 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. 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). To note that Patra et al. (2016) used an earlier version of the ACTM (now changed to MIROC4-ACTM; Patra et al., 2018). However, Chadra et al. (2021) used the newer MIROC4-ACTM, using ensemble of inversions by varying prior flux uncertainties and data uncertainties input to the inversion model rather than a single inversion case as in Chandra et al., 2021. According to Chandra et al., 2021, the changes in anthropogenic emissions have dominated the contributions to the three different CH_4 growth rate phases from 1988 to 2016, whereas natural emissions likely dominated the IAV in CH_4 emissions.

For ***Indonesia****,* most TD results agree and show a slight increase in emissions. Similar trend is also seen by the BURs.

For ***Russia***, the estimates from CIF FLEXPART_NILU and FLEXkF_v2023 are provided only for the European Russian part. The other global estimates are in the same range as the BU GAINS estimate (see Figure 2), between 30-40 Tg CH_4 yr^{-1}). They mostly belong to emissions from natural sources (e.g., wetlands and anthropogenic other than rice, Figure 5).

DR Congo*:* Except for TROPOMI, all other inversions agree well on magnitude and trends.

Figure 4 summarizes the fluxes from BU anthropogenic sources, disaggregated per sectors, BU natural, TD natural partitions, and TD total fluxes. We hypothesize that one reason for differences seen for the TD natural fluxes are due to the different allocations of the natural fluxes in the TD partitions. We note the following: for USA CTE_GCP2021 underestimates a lot the natural TD flux belonging to the Wetlands MIROC includes Rice in Agriculture (Anthropogenic partition) and CTE reports Rice and BB in Anthropogenic, impossible to compare same things, see harmonization in Figure 6 and Table 3.

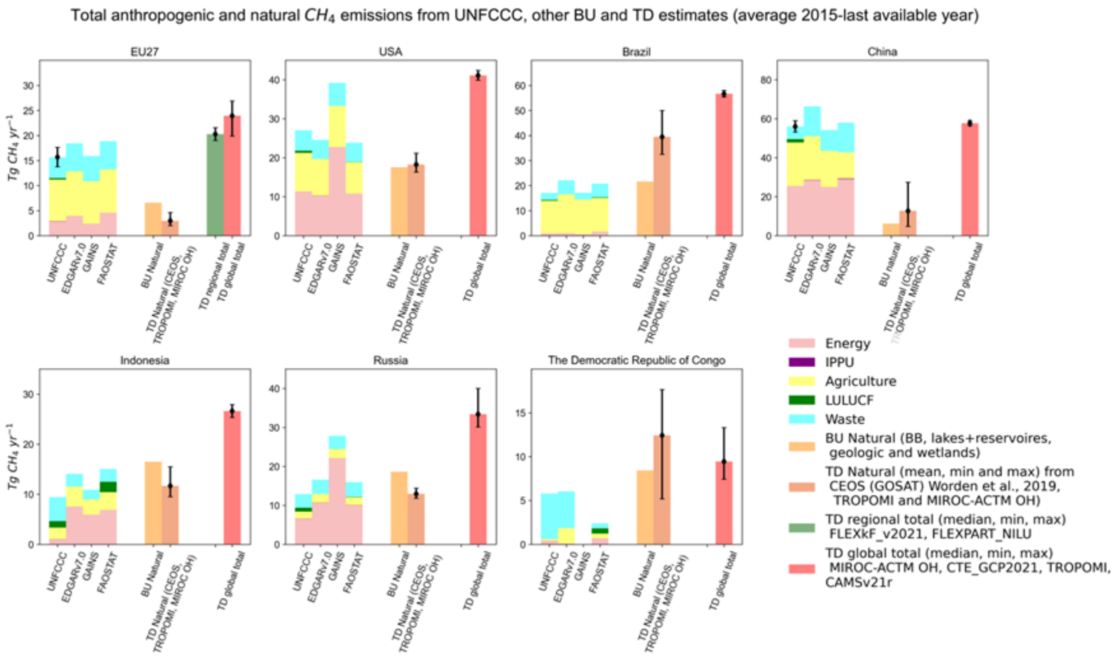

Figure 4: ***Total anthropogenic and natural CH_4 emissions from BU and TD estimates for EU27 and six global emitters (USA, Brazil, China, Indonesia, Russia and DR Congo). The BU anthropogenic estimates belong to: UNFCCC CRFs and BURs as totals and sectoral shares, EDGARv7.0, GAINS and FAOSTAT. The relative error on the UNFCCC CRF value represents the NGHGI (2021) 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., 2023, Appendix). In 2014, China reports as well an uncertainty of min 5.2% max 5.3%. The BU Natural emissions for EU27 are the sum of the VERIFY products (biomass burning, inland waters, geologic and peatlands plus mineral soils as described in Petrescu et al., 2021 and 2023). For the six global emitters, the BU Natural fluxes are the sum of wetland emissions (LPJ-GUESS), lakes and reservoirs fluxes (ORNL DAAC) and biomass burning emissions (GFED4.1). The TD Natural global estimates are the average of the CEOS (GOSAT) estimates for the year 2019 (Worden et al., 2019) (wetlands) + geological (Etiope 2023)), TROPOMI partitions (sum of wetlands, rice and biomass burning fluxes) and MIROC-ACTM OH varying runs partitions (wetlands, termites, ocean, biomass burning, soils and geologic. The uncertainty on the TD natural is the min/max of CEOS, TROPOMI and MIROC estimates. The total regional TD estimates (for EU27) belong to the median and min/max of FELXkF_v2023 and FLEXPART_NILU (VERIFY-CIF). The total global TD inversions are the median and min/max of CTE-GCP2021, MIROC4-ACTM (control and OH varying runs), CAMS v21r and TROPOMI. Last available years are: UNFCCC CRFs, TROPOMI, FEXPART_NILU (CIF) (2020) and FLEXkF_v20203, MIROC-ACTM both runs, CTE-GCP2021 and CAMSv21r both runs (2021).***

The following Tables 2 and 3 and Figures 5 and 6 show the partitions reported by some of the TD inversions. Table 2 shows the partitions and the way TD inversions report it. Table 3 shows the partitions harmonized between products.

Table 2: ***Raw unharmonized partitions originally reported by inverse products:***

Inver sion	Anthrop ogenic	ice	oils	We tlands	cean	Te rmites	Ge ologic	Bio mass burning	Other
MIR OC-ACTM (OH)	Yes ((Agr, Waste, Oil/Gas, Biofuel, coal)	es (in Agr.)	es	Yes	Y es	Ye s	Ye s	Yes	N/A
CTE-GCP2021*	Yes (Agr, waste, fossil fuel, biofuel, biomass burning)	es (in Agr.)	Yes (BIO)		N o	No	No	In anthr.	Yes (Ocean,Termites,Geologic)
CEO S (GOSAT)	Yes (Livestock, rice, waste, coal, oil, fire)	n anthr.	o	Yes	N o	No	Ye s (seeps)	In anthr.	No
TRO POMI	Yes (in other)	es	o	Yes	Y es (in other)	Ye s (in other)	No	Yes	Yes**

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

** In TROPOMI (similar to the CAMSv20 set-up), the "other" partition refers to all sources except for the rice paddies. It also includes the small fluxes from termites, oceans, soil sink etc.).

More details on priors are found in Appendix, Table A2.

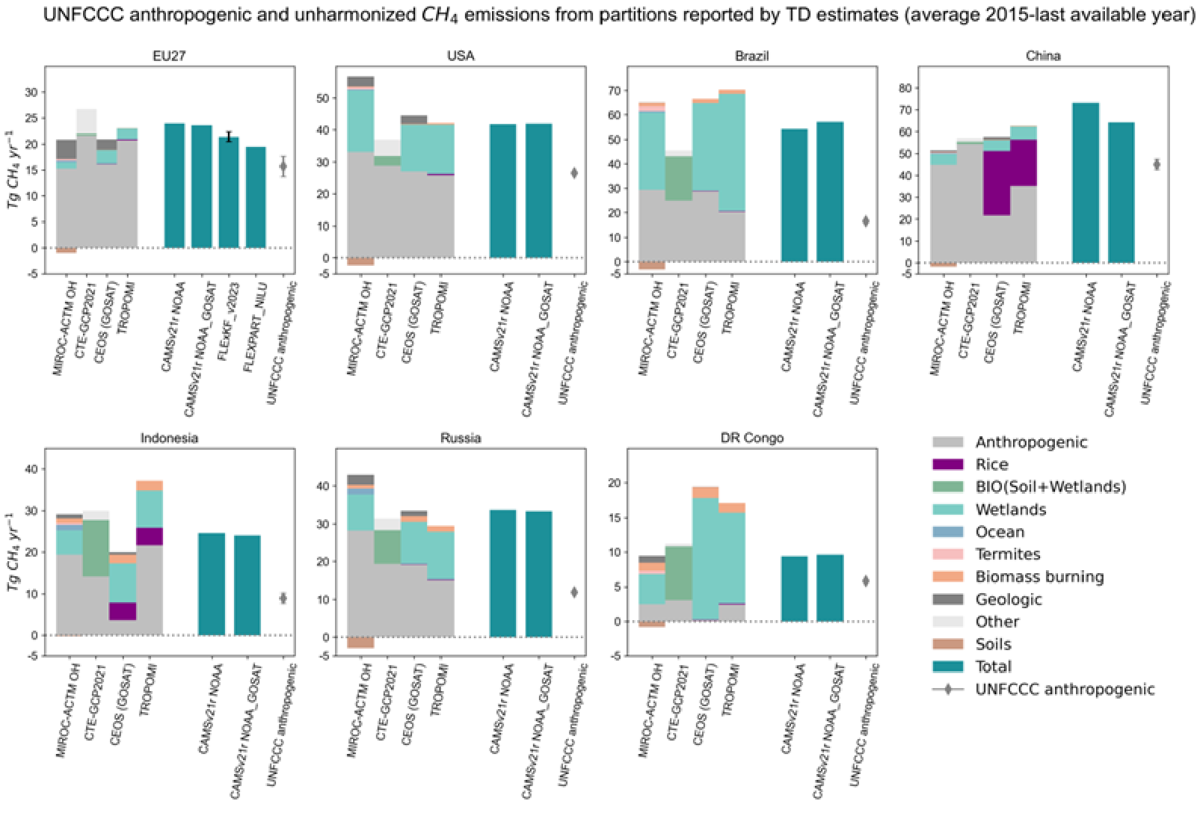

Figure 5: ***Total and disaggregated anthropogenic and natural CH_4 emissions from TD estimates compared to UNFCCC anthropogenic for the EU27 and six global emitters (USA, Brazil, China, Indonesia, Russia and DR Congo). The UNFCCC anthropogenic value represents the sum of all 5 IPCC sectors (Energy, 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 (2021) 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., 2023, Appendix). In 2014, China reports as well an uncertainty of min 5.2% max 5.3%. China reports uncertainties for 2014 (min 5.2 %, max 5.3 %) and Indonesia***

for 2000 and 2019 (13.8 %). The plotted data represents the average between 2015 and last available reported year as follows: UNFCCC CRFs, TROPOMI, FEXPART_NILU (CIF) (2020) and FLEXkF_v2023, MIROC-ACTM both runs, CTE-GCP2021 and CAMSv21r both runs (2021).

Table 3*: Harmonized and grouped partitions from inverse products:*

Harmonized partitions	Anthropogenic + Rice + BB			Soils + Wetlands		Other (Ocean + Termites + Geologic)		
	Anthropogenic	**Rice**	**Biomass burning**	**Soils**	**Wetlands**	**Ocean**	**Termites**	**Geologic**
MIROC-ACTM (OHvar)	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 (seeps)
TROPOMI	Others + Rice+ BB	In anthr.	Yes, summed to anthr.	No	Yes	Yes	Yes	No

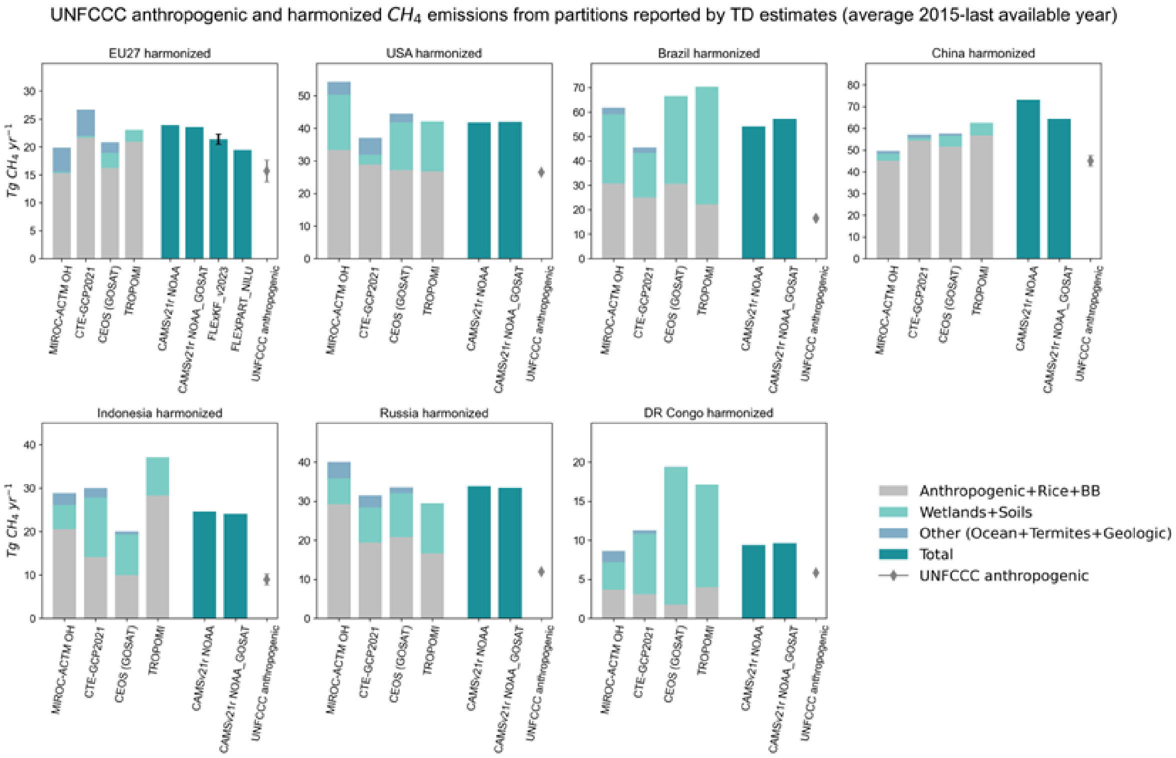

Figure 6*: Total and disaggregated anthropogenic and natural CH4 emissions from TD estimates compared to UNFCCC anthropogenic for the EU27 and six global emitters (USA, Brazil, China, Indonesia, Russia and DR Congo). The UNFCCC anthropogenic value represents the sum of all 5 IPCC sectors (Energy, IPPU, 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 (2021) 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., 2023, Appendix). In 2014, China reports as well an uncertainty of min 5.2% max 5.3%. China reports uncertainties for 2014 (min 5.2 %, max 5.3 %)*

and Indonesia for 2000 and 2019 (13.8 %). The plotted data represents the average between 2015 and last available reported year as follows: UNFCCC CRFs, TROPOMI, FEXPART_NILU (CIF) (2020) and FLEXkF_v2023, MIROC-ACTM both runs, CTE-GCP2021 and CAMSv21r both runs (2021).

5 Summary and conclusions

1. The current study analyzed data from both anthropogenic and natural CH_4 fluxes, from both bottom-up and top-down observation-based estimates (see Table 1).
2. Bottom-up estimates show that the largest CH_4 emissions are from the agricultural sector primarily livestock (enteric fermentation), followed by Waste sector (Figure 4). The top-down inversions (Figure 4) attribute as well most of the fluxes to the anthropogenic emissions (grey) (EU27, China) while in tropical countries they mostly belong to natural sources (wetlands, rice).
3. Compared to the global total anthropogenic CH_4 emissions (386 Tg CH_4 / yr) reported by EDGARv7.0, the EU27 and the six countries analyzed here contribute a third of anthropogenic emissions (130 Tg CH_4 / yr - sum of last UNFCCC reported year) while the total averaged atmospheric inversions (anthropogenic partition) report 149 Tg CH_4/ yr (grey part, Figure 5).
4. It is challenging to reconcile between BU and TD estimates, due to different priors used in the simulations (see Appendix, Table A2). Also challenging is the comparison between different TD products due to the allocation fluxes to different activities and sectors/sources (see Table 2).
5. Despite comparability issues highlighted in section 2.3 and Table A1, we find comparison between UNFCCC – BU (Figure 2) valid. The deviations from BU estimates compared to the NGHGIs (Figure 2) are mainly due to assumptions regarding gas/oil emissions (e.g., GAINS for Russia, USA).
6. The comparison between UNFCCC – TD (Figure 3) is acceptable, even if, in most cases the UNFCCC BURs report underestimated CH_4 fluxes for non-Annex I parties (China, Indonesia, DR Congo) compared to the total TD estimates, but this is due to the reporting of the anthropogenic component only.
7. From Figure 4 we note that the gap between the anthropogenic and total TD fluxes can be filled by the natural fluxes.
8. The allocation of fluxes to different categories (Figure 5) is correct for most countries (clear distinction between developing industrialized countries (China), tropical natural based (Brazil, DR Congo) or mixed sourced sectoral developed countries such USA and Russia. Also, the contribution of emissions from rice paddies and fires is well captured in Indonesia.
9. There is still a great need of better estimation of uncertainties in both prior and posterior emissions, even if some TD inversions do calculate it (CTE-GCP2021, Figure 3) and is represented as the standard deviation if ensemble members.

For CH_4 emissions, we make comparisons with a variety of inventory-based estimates and inversions. CH_4 emissions have increased in the last three decades, but have declined in the USA and EU (regulations) and Russia (dissolution of the Soviet Union). For the inventories, divergences between data sets can generally be attributed to different methodology and tiers used by each of the investigated inventories, when data is available to make comparisons (such as activity data and emission factors). The use of a variety of priors across different inversion systems can also inhibit comparability with inventories and between inversions.

For the inversions, the general magnitudes and trends agree, but uncertainties are too large to be more specific. However, the split in anthropogenic and natural components helped explaining some differences. For a more robust analysis, more detail is needed on prior and posterior uncertainties, to help identify statistically significant differences between datasets.

6 Appendix

All the information regarding country plots and model descriptions will be prepared and provided later in a Supplementary Information (SI) file.

Table A1: Matrix highlighting the comparability issues identified in section 3.4:

Products	System boundary: Country borders	System boundary: Land definitions (managed, unmanaged)	System boundary: Lateral flux (inland waters)	National estimates	Temporal resolution	Spatial resolution	Trends / variability	Priors	Aggregation (country, region)	Statistical significance (uncertainty)	Model ensembles	Anthropogenic fluxes	Natural fluxes	Standardisation
bottom-up approaches: anthropogenic														
UNFCCC NGHGI CRFs	yes	yes, IPCC	N/A	yes	annual	N/A	annual	IPCC defaults or country specific	manual	yes	N/A	yes	N/A	yes
UNFCCC NGHGI BURs	yes	yes, IPCC	N/A	yes	annual	N/A	irregular	IPCC defaults or country specific	manual	partially	N/A	yes	N/A	yes
FAOSTAT	yes	yes, IPCC	N/A	yes	annual	N/A	annual	AD, EF (IPCC or source specific)	manual	N/A	N/A	yes	N/A	yes
GAINS	yes	N/A	N/A	yes	annual	N/A	annual	AD, EF (IPCC or source specific)	manual	N/A	N/A	yes	N/A	yes
EDGARv7.0	yes	yes, IPCC	N/A	yes	monthly	0.1°x0.1° [3]	annual	AD, EF (IPCC or source specific)	manual	2015	N/A	yes	N/A	yes
bottom-up approaches: natural														
JSBACH-HIMMELI [1]	N/A	N/A	N/A	indirect [4]	daily	0.1°x0.1° [3]	seasonal	bottom-up specific	manual	N/A	N/A	N/A	yes	N/A
LPJ-GUESS [2] (natural wetlands)	N/A	N/A	N/A	indirect [4]	monthly	0.5°x0.5° [3]	seasonal	bottom-up specific	manual	N/A	N/A	N/A	yes	N/A
Inland water fluxes (ULB, RECCAP2) [1], DAAC [2]	N/A	N/A	yes	indirect [4]	annual	?	annual	bottom-up specific	manual	N/A	N/A	N/A	yes	N/A
Biomass burning (GFEDv4.1s) [2]	N/A	N/A	N/A	indirect [4]	daily	0.25°x0.25° [3]	seasonal	bottom-up specific	manual	N/A	N/A	N/A	yes	N/A
Geological fluxes [2]	N/A	N/A	N/A	indirect [4]	decadal	1°x1° [3]	no	bottom-up specific	manual	N/A	N/A	N/A	yes	N/A
top-down approaches														
FLEXKF_EMPA [1]	N/A	N/A	included	indirect [4]	monthly	0.5°x0.5° [3]	seasonal	EDGARv6.0, JSBACH-HIMMELI and source specific	manual	only posterior	N/A	priors	priors	N/A
CTE-CH_4 (GCP2021) [2]	N/A	N/A	included	indirect [4]	monthly	1°x1° [3]	seasonal	EDGARv4.3, JSBACH-HIMMELI and source specific	manual	prior, posterior	N/A	priors	partitions	N/A
VERIFY CIF (CHIMERE, FLEXPART v10.4_NILU and FELXPART_EMPA) [1]	N/A	N/A	included	indirect [4]	monthly	0.25°x0.25° [3]	seasonal	EDGARv6.0, JSBACH-HIMMELI and source specific	manual	only prior	yes	priors	partitions	partially
CAMS v21r [2]	N/A	N/A	included	indirect [4]	monthly	3°x2° [3]	seasonal	EDGARv6.0 and source specific	manual	prior, posterior	N/A	priors	partitions	N/A
TROPOMI [2]	N/A	N/A	included	indirect [4]	monthly	6°x4° [3]	seasonal	CAMS v20r	TRANS-COM regions	N/A	N/A	priors	partitions	N/A
MIROC4-ACTM (control and OH varying) [2]	N/A	N/A	included	indirect [4]	monthly	1°x1° [3]	seasonal	EDGARv6.0 and source specific	manual	only prior	N/A	priors	partitions	N/A
CEOS (Worden et al., 2019) GOSAT [2]														

N/A = not available, applicable

1= regional

2= global

3= gridded information

4= indirect from gridded info (using country masks)

soource specific refers to table X PRIORS

Table A2: Priors used by BU and TD approaches

Products	Category: Peatlands, Wetlands, Innundated soils ≤ 1989	Peatlands, Wetlands, Innundated soils 1990-2020	Peatlands, Wetlands, Innundated soils ≥ 2021	Mineral soils	Rice 1989-1999	Rice 2000-2018	Rice ≥ 2019	(Biofuels and) Biomass Burning (BB) ≤ 2002	(Biofuels and) Biomass Burning (BB) ≥ 2003	other anthropogenic 1989-1990	other anthropogenic 2000-2018	other anthropogenic ≥ 2019	oceans climatology	lakes	wild animals climatology	soil sink climatology	termites climatology	geologic
CAMS v21r	(1990)	LPF-wsl (wetlands)	(2020)	N/A	EDGARv6.0 with 2000 seasonality	EDGARv6.0 with monthly temporal resolution	EDGARv6.0 with 2018 seasonality, extrapolated	ACCMIP-MACCity	GFAS	EDGARv6.0 with 2000 seasonality	EDGARv6.0 with monthly temporal resolution	EDGARv6.0 with 2018 seasonality, extrapolated	Lambert	N/A	Olson	Ridgwell	Sanderson	N/A
CTE-CH_4 VERIFY (Petrescu et al., 2021)	LPX-Bern DYPTOP (Stocker et al., 2014)				EDGAR v4.2 FT2010 (Janssens-Maenhout et al., 2013)			GFEDv4		EDGAR v4.2 FT2010 (Janssens-Maenhout et al., 2013)			Lambert and Schmidt (1993), ECMWF Era-Interim (as in Tsuruta et al., 2017)	ULB model	N/A	JSBACH-HIMMELI	Ito and Inatomi (2012)	Etiope et al., 2019 scaled down to a global total of 15 Tg/y in accordance with Petrenko et al. 2017
CTE-CH_4 S5 (core)	JSBACH-HIMMELI (Peatlands and innundated)			JSBACH-HIMMELI	EDGARv6.0			GFEDv4.1s		EDGARv6.0			Weber et al., 2019	ULB model	N/A	JSBACH-HIMMELI	Castaldi as GCP	Etiope et al., 2019 scaled down to a global total of 15 Tg/y in accordance with Petrenko et al. 2017
CTE-CH_4 SURF	Global Carbon Project (Saunois et al., 2020)			Global Carbon Project (Saunois et al., 2020)	EDGARv4.3.2			GFEDv41s		EDGARv4.3.2			Weber et al., 2019	N/A	N/A	Global Carbon Project (Saunois et al., 2020)	Ito and Inatomi (2012)	Etiope et al., 2019
CTE-CH_4 GOSAT				Global Carbon Project (Saunois et al., 2020)	EDGARv4.3.2			GFEDv41s		EDGARv4.3.2			Weber et al., 2019	N/A	N/A	Global Carbon Project (Saunois et al., 2020)	Ito and Inatomi (2012)	
CTE-CH_4 IG^{3}IS	JSBACH-HIMMELI 0.1°x 0.1° daily 2005-2018				EDGAR v6.0 0.1°x 0.1° monthly 2005-2018 (agriculture)			GFED-4.1s 0.25°x 0.25° monthly 2005-2018		EDGAR v6.0 0.1°x 0.1° monthly 2005-2018 (fossil fuels), EDGAR v6.0 0.1°x 0.1° monthly 2005-2018 (waste)			Weber, 2021 (annually, climatology)	ULB 0.1°x 0.1° (annually, climatology)	N/A	N/A	Castaldi, 2013 (annually, climatology)	Etiope, 2015 (annually, Climatology)
CTE-CH_4 GCP2021	GCP Dynamical wetlands emissions from the GMB BU group: mean of 11 models contributing Saunois et al 2020 al. (2020)			Saunois et al., 2020	EDGARv6.0			EDGARv6.0 (biofuel) and GFEDv41s (BB)		Oil and Gas from GAINS, Others from EDGARv6.0			Weber et al., 2019	Stavert et al. (2021) as GCP scaled to 50 Tg	EDGARv6.0	Saunois et al., 2020	Castaldi as GCP	Etiope et al. (2019) gridded files scaled to 23 Tg
VERIFY CIF (FEXPART_NILU, FLEXPART_EMPA and CHIMERE)	JSBACH-HIMMELI (Peatlands and innundated)			JSBACH-HIMMELI	EDGARv6.0			EDGARv6.0 (biofuel) and GFEDv41s (BB)		EDGARv6.0 (Agriculture and Waste)			Weber et al., 2019	CSLM-CH4 model	N/A	JSBACH-HIMMELI	Castaldi as GCP	Etiope et al., 2019
FLEXKF v2021 (VERIFY)	JSBACH-HIMMELI (Peatlands and innundated)			JSBACH-HIMMELI	EDGARv6.0			EDGARv6.0 (biofuel) and GFEDv41s (BB)		EDGARv6.0 (Agriculture and Waste)			Weber et al., 2019	ULB model	N/A	Ridgwell /GCP	Ito and Inatomi (2012)	Etiope et al., 2019
MIROC4-ACTM	VISIT (Ito and Inatomi, 2012)				VISIT (Ito and Inatomi, 2012)			GFEDv41s		Oil and Gas from GAINS, Others from EDGARv6.0			Weber et al., 2019	N/A	EDGARv6.0	VISIT (Ito and Inatomi, 2012)	Castaldi as GCP	Etiope and Milkov, 2004
TROPOMI	LPF-wsl			N/A	EDGARv6.0 with 2000 seasonality	EDGARv6.0 with monthly temporal resolution	EDGARv6.0 with 2018 seasonality, extrapolated	ACCMIP-MACCity	GFAS	EDGARv6.0 with 2000 seasonality	EDGARv6.0 with monthly temporal resolution	EDGARv6.0 with 2018 seasonality, extrapolated	Lambert	N/A	Olson	Ridgwell	Sanderson	N/A
CEOS, Worden et al., 2019 (GOSAT)	WetCHARTS v1.3.1 18-member ensemble mean (Bloom et al., 2017)			N/A	Seasonality: Maasakkers et al. (2016) and Zhang et al. (2016)			GFEDv4s		Manure seasonality (Maasakkers et al. (2016) and Zhang et al. (2016)); EDGAR v4.3.2			N/A	N/A	N/A	N/A	Fung et al. (1991)	Hmiel et al. (2020) with the spatial distribution from Etiope et al. (2019)

7 References

Andrew, Robbie M. 2020. “A Comparison of Estimates of Global Carbon Dioxide Emissions from Fossil Carbon Sources.” *Earth System Science Data* 12 (2): 1437–65. https://doi.org/10.5194/essd-12-1437-2020.

Balcombe P., Speirs J.F., Brandon N.P., Hawkes A.D. Methane emissions: choosing the right climate metric and time horizon, Environ Sci Process Impacts, 20 (10), pp. 1323-1339, 2018.

Berchet, A., Sollum, E., Thompson, R. L., Pison, I., Thanwerdas, J., Broquet, G., Chevallier, F., Aalto, T., Berchet, A., Bergamaschi, P., Brunner, D., Engelen, R., Fortems-Cheiney, A., Gerbig, C., Groot Zwaaftink, C. D., Haussaire, J.-M., Henne, S., Houweling, S., Karstens, U., Kutsch, W. L., Luijkx, I. T., Monteil, G., Palmer, P. I., van Peet, J. C. A., Peters, W., Peylin, P., Potier, E., Rödenbeck, C., Saunois, M., Scholze, M., Tsuruta, A., and Zhao, Y.: The Community Inversion Framework v1.0: a unified system for atmospheric inversion studies, Geosci. Model Dev., 14, 5331–5354, https://doi.org/10.5194/gmd-14-5331-2021, 2021.

Bergamaschi, P., Karstens, U., Manning, A. J., Saunois, M., Tsuruta, A., Berchet, A., Vermeulen, A. T., Arnold, T., Janssens-Maenhout, G., Hammer, S., Levin, I., Schmidt, M., Ramonet, M., Lopez, M., Lavric, J., Aalto, T., Chen, H., Feist, D. G., Gerbig, C., Haszpra, L., Hermansen, O., Manca, G., Moncrieff, J., Meinhardt, F., Necki, J., Galkowski, M., O'Doherty, S., Paramonova, N., Scheeren, H. A., Steinbacher, M., and Dlugokencky, E.: Inverse modelling of European CH_4 emissions during 2006–2012 using different inverse models and reassessed atmospheric observations, Atmos. Chem. Phys., 18, 901–920, https://doi.org/10.5194/acp-18-901-2018, 2018.

Brazil, BUR 4, 2020: https://unfccc.int/documents/267661

Chandra et al., 2021: Journal of the Meteorological Society of Japan, 99(2), 309−337, 2021. doi:10.2151/jmsj.2021-015

China BUR 2, 2019: https://unfccc.int/documents/197666

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., and Janssens-Maenhout, G.: High resolution temporal profiles in the Emissions Database for Global Atmospheric Research, Sci. Data, 17, 121, https://doi.org/10.1038/s41597-020-0462-2, 2020.

D8.4 CoCO$_2$ report: https://coco2-project.eu/node/355

Deng, Zhu, Philippe Ciais, Zitely A. Tzompa-Sosa, Marielle Saunois, Chunjing Qiu, Chang Tan, Taochun Sun, et al. 2022. “Comparing National Greenhouse Gas Budgets Reported in UNFCCC Inventories against Atmospheric Inversions.” *Earth System Science Data* 14 (4): 1639–75. https://doi.org/10.5194/essd-14-1639-2022.

DR Congo, BUR 1, 2022: https://unfccc.int/documents/624762

Evans and Roshchanka: Russian policy on methane emissions in the oil and gas sector: A case study in opportunities and challenges in reducing short-lived forcers, Volume 92, August 2014, Pages 199-206 https://doi.org/10.1016/j.atmosenv.2014.04.026, 2014

Grassi, Giacomo, Elke Stehfest, Joeri Rogelj, Detlef van Vuuren, Alessandro Cescatti, Jo House, Gert-Jan Nabuurs, et al. 2021. “Critical Adjustment of Land Mitigation Pathways for Assessing Countries’ Climate Progress.” *Nature Climate Change* 11 (5): 425–34. https://doi.org/10.1038/s41558-021-01033-6.

Gütschow, J.; Pflüger, M. (2021): The PRIMAP-hist national historical emissions time series v2.4 (1750-2021). zenodo. doi:10.5281/zenodo.7179775

Höglund-Isaksson, L.: Bottom-up simulations of methane and ethane from global oil and gas systems, Environ. Res. Lett., 12, 024007, https://doi.org/10.1088/1748-9326/aa583e, 2017.

Höglund-Isaksson L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., and Schöpp, W.: Technical potentials and costs for reducing global anthropogenic methane emissions in the

2050 timeframe – results from the GAINS model, Environ. Res. Commun., 2, 025004, https://doi.org/10.1088/2515-7620/ab7457, 2020.

Huang, K. et al., 2015. Russian anthropogenic black carbon: Emission reconstruction and Arctic black carbon simulation. *Journal of Geophysical Research: Atmospheres* DOI:10.1002/2015JD023358.

Indonesia, BUR 3, 2021: https://unfccc.int/documents/403577

IPCC 2006. *IPCC Guidelines for National Greenhouse Gas InventoriesInventories, Prepared by the National Greenhouse Gas Inventories Programme*. Edited by H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Japan: IGES. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

IPCC 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Edited by E. Calvo Buendia, K. Tanabe, A. Kranje, B. Jamsranjav, M. Fukuda, S. Ngarize, A. Osaka, Y. Pyrozhenko, P. Shermanau, and S. Federici. Switzerland: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

IPCC: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, available at: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories (last access: January 2020), 2019b.

IPCC: Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, edited by: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T. G., IPCC, Switzerland, 2014.

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

IPCC Guidelines for National Greenhouse Gas Inventories (NGHGI): https://www.ipcc-nggip.iges.or.jp/public/2006gl/ (last access: January 2022), 2006.

IPCC: vol. 1, chap. 3, https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf (last access: June 2022), 2006.

National Academies of Sciences, Engineering, and Medicine. 2022. *Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26641.

UNFCCC NGHGI: NIR reports: UNFCCC: National Inventory Submissions 2022, https://unfccc.int/ghg-inventories-annex-i-parties/2022 last access: May 2022.

Nisbet, E.G. Climate feedback on methane from wetlands. *Nat. Clim. Chang.* (2023). https://doi.org/10.1038/s41558-023-01634-3

NOAA: https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021

Patra, P. K., Saeki, T., Dlugokencky, E. J., Ishijima, K., Umezawa, T., Ito, A., Aoki, S., Morimoto, S., Kort, E. A., Crotwell, A., Ravikumar, K., and Nakazawa, T.: Regional methane emission estimation based on observed atmospheric concentrations (2002–2012), J. Meteorol. Soc. Jpn., 94, 91–113, 2016.

Patra, P. K., Takigawa, M., Watanabe, S., Chandra, N., Ishijima, K., and Yamashita, Y.: Improved Chemical Tracer Simulation by MIROC4.0-based Atmospheric Chemistry-Transport Model (MIROC4-ACTM), SOLA, 14, 91–96, 2018.

Patra, P.K. et al., 2021: Methyl Chloroform Continues to Constrain the Hydroxyl (OH) Variability in the Troposphere. *Journal of Geophysical Research: Atmospheres*, **126(4)**, e2020JD033862, doi: 10.1029/2020jd033862.

Peng, S., Lin, X., Thompson, R.L. *et al.* Wetland emission and atmospheric sink changes explain methane growth in 2020. *Nature* 612, 477–482 (2022). https://doi.org/10.1038/s41586-022-05447-w

Petrescu, Ana Maria Roxana, Matthew J. McGrath, Robbie M. Andrew, Philippe Peylin, Glen P. Peters, Philippe Ciais, Gregoire Broquet, et al. 2021. "The Consolidated European Synthesis of CO_2 Emissions and Removals for the European Union and United Kingdom: 1990–2018." *Earth System Science Data* 13 (5): 2363–2406. https://doi.org/10.5194/essd-13-2363-2021.

Petrescu, Ana Maria Roxana, Glen P. Peters, Greet Janssens-Maenhout, Philippe Ciais, Francesco N. Tubiello, Giacomo Grassi, Gert-Jan Nabuurs, et al. 2020. "European Anthropogenic AFOLU Greenhouse Gas Emissions: A Review and Benchmark Data." *Earth System Science Data* 12 (2): 961–1001. https://doi.org/10.5194/essd-12-961-2020.

Petrescu, Ana Maria Roxana, Chunjing Qiu, Philippe Ciais, Rona L. Thompson, Philippe Peylin, Matthew J. McGrath, Efisio Solazzo, et al. 2021. "The Consolidated European Synthesis of CH_4 and N_2O Emissions for the European Union and United Kingdom: 1990–2017." *Earth System Science Data* 13 (5): 2307–62. https://doi.org/10.5194/essd-13-2307-2021.

Petrescu, Ana Maria Roxana, Chunjing Qiu, Matthew J. McGrath, Philippe Peylin, Glen P. Peters, Philippe Ciais, Rona L. Thompson, et al. 2022. "The Consolidated European Synthesis of CH_4 and N_2O Emissions for EU27 and UK: 1990–2020." *Earth System Science Data Discussions*, September, 1–97. https://doi.org/10.5194/essd-2022-287.

Regulation (EU): 525/2013 of the European Parliament and of the Council, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0525&from=EN, last access: November 2020.

Saunois, Marielle, Ann R. Stavert, Ben Poulter, Philippe Bousquet, Josep G. Canadell, Robert B. Jackson, Peter A. Raymond, et al. 2020. "The Global Methane Budget 2000–2017." *Earth System Science Data* 12 (3): 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.

Solazzo, Efisio, Monica Crippa, Diego Guizzardi, Marilena Muntean, Margarita Choulga, and Greet Janssens-Maenhout. 2021. "Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) Emission Inventory of Greenhouse Gases." *Atmospheric Chemistry and Physics* 21 (7): 5655–83. https://doi.org/10.5194/acp-21-5655-2021.

Stavert, A. R., Saunois, M., Canadell, J. G., Poulter, B., Jackson, R. B., Regnier, P., Lauerwald, R., Raymond, P. A., Allen, G. H., Patra, P. K., Bergamaschi, P., Bousquet, P., Chandra, N., Ciais, P., Gustafson, A., Ishizawa, M., Ito, A., Kleinen, T., Maksyutov, S., … Zhuang, Q. (2022). Regional trends and drivers of the global methane budget. *Global Change Biology*, 28(1), 182– 200. https://doi.org/10.1111/gcb.15901

UNFCCC: National Inventory Submissions 2019, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019 (last access: September 2020), 2019.

UNFCCC: National Inventory Submissions 2018, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018 (last access: January 2020), 2018.

United Nations Environment Programme & Climate & Clean Air Coalition, 2021: https://www.unep.org/explore-topics/climate-action/what-we-do/climate-and-clean-air-coalition-ccac

VERIFY D6.13: https://projectsworkspace.eu/sites/VERIFY/Deliverables/WP6/VERIFY_D6.13_Online%20representation%20of%20the%20geographic%20distribution%20of%20GHG%20emissions%20and%20sinks%20uncertainties_v1.pdf

Wolf, J., G. R. Asrar, and T. O. West, 2017: Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance Manage.*, 12, 16, doi:10.1186/s13021-017-0084-y.

7 APPENDIX B: CO2 synthesis

The consolidated European synthesis of CO_2 emissions and removals for the European Union: 1990-2021

Matthew J. McGrath[1], Ana Maria Roxana Petrescu[2], Philippe Peylin[1], Robbie M. Andrew[3], Bradley Matthews[4], Frank Dentener[5], Juraj Balkovič[6], Vladislav Bastrikov[7], Meike Becker[8,9], Gregoire Broquet[1], Philippe Ciais[1], Audrey Fortems[1], Raphael Ganzenmüller[10], Giacomo Grassi[5], Ian Harris[11], Matthew Jones[12], Juergen Knauer[13], Matthias Kuhnert[14], Guillaume Monteil[15], Saqr Munassar[16], Paul I. Palmer[17], Glen P. Peters[3], Chunjing Qiu[1], Mart-Jan Schelhaas[18], Oksana Tarasova[19], Matteo Vizzarri[5], Karina Winkler[18,20], Gianpaolo Balsamo[21], Antoine Berchet[1], Peter Briggs[13], Patrick Brockmann[1], Frédéric Chevallier[1], Giulia Conchedda[22], Monica Crippa[5], Stijn Dellaert[23], Hugo A. C. Denier van der Gon[23], Sara Filipek[18], Pierre Friedlingstein[24], Richard Fuchs[20], Michael Gauss[25], Christoph Gerbig[16], Diego Guizzardi[5], Dirk Günther[26], Richard A. Houghton[27], Greet Janssens-Maenhout[5], Ronny Lauerwald[28], Bas Lerink[18], Ingrid T. Luijkx[18], Géraud Moulas[29], Marilena Muntean[5], Gert-Jan Nabuurs[18], Aurélie Paquirissamy[1], Lucia Perugini[30], Wouter Peters[18], Roberto Pilli[31], Julia Pongratz[10,32], Pierre Regnier[33], Marko Scholze[15], Yusuf Serengil[34], Pete Smith[14], Efisio Solazzo[ex(5)], Rona L. Thompson[35], Francesco N. Tubiello[22], Timo Vesala[36,37], Sophia Walther [16]

[1]Laboratoire des Sciences du Climat et de l'Environnement, CEA CNRS UVSQ UPSACLAY Orme des Merisiers, Gif-sur-Yvette, France
[2]Department of Earth Sciences, Vrije Universiteit Amsterdam, 1081HV, Amsterdam, the Netherlands
[3]CICERO Center for International Climate Research, Oslo, Norway
[4]Environment Agency Austria, Spittelauer Lände 5 1090, Vienna, Austria
[5]European Commission, Joint Research Centre, Via E. Fermi, 2749, TP 26/A, 21027, Ispra, Italy
[6]International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria
[7]Science Partners, 75010 Paris, France
[8]Geophysical Institute, University of Bergen, Bergen, Norway
[9]Bjerknes Centre for Climate Research, Bergen, Norway
[10]Department of Geography, Ludwig-Maximilians-Universität München, Luisenstraße 37, 80333 München, Germany
[11]National Centre for Atmospheric Science (NCAS), University of East Anglia, Norwich, United Kingdom; and Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
[12]Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich Research Park,Norwich NR4 7TJ, United Kingdom
[13]Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
[14]Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK
[15]Dept. of Physical Geography and Ecosystem Science, Lund University
[16]Max Planck Institute for Biogeochemistry, Hans-Knöll-Strasse 10, 07745 Jena, Germany
[17]School of GeoSciences, University of Edinburgh, Edinburgh, UK
[18]Wageningen Environmental Research, Wageningen University and Research (WUR), Wageningen, 6708PB, the Netherlands
[19]Science and Innovation Department, World Meteorological Organization (WMO), Geneva, Switzerland
[20]Land Use Change & Climate Research Group, IMK-IFU, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[21]European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, RG2 9AX, UK
[22]FAO, Statistics Division, Via Terme di Caracalla, Rome 00153, Italy
[23]Department of Climate, Air and Sustainability, TNO, Princetonlaan 6, 3584 CB Utrecht, the Netherlands
[24]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, UK
[25]Norwegian Meteorological Institute, Oslo, Norway
[26]Umweltbundesamt (UBA), 14193 Berlin, Germany
[27]Woodwell Climate Research Center, Falmouth, Massachusetts, U.S.A.
[28]Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Thiverval-Grignon, France
[29]ARTTIC, 39 rue des Mathurins, 75008 Paris, France
[30]Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Viterbo, Italy
[31]Scientific consultant, Padua, Italy
[32]Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[33]Biogeochemistry and Modeling of the Earth System, Université Libre de Bruxelles, 1050 Bruxelles, Belgium
[34]Istanbul University, Faculty of Forestry, Department of Watershed Management, 34473 Sariyer, Istanbul, Turkey
[35]Norwegian Institute for Air Research (NILU), Kjeller, Norway
[36]University of Helsinki, Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, 00560 Helsinki, Finland
[37]Institute for Atmospheric and Earth System Research,/Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland

1 Abstract

Quantification of land surface-atmosphere fluxes of carbon dioxide (CO_2) fluxes and their trends and uncertainties is essential for monitoring progress of the EU27 bloc as it strives to meet ambitious targets determined by both international agreements and internal regulation. This study provides a consolidated synthesis of fossil sources (CO_2 fossil) and natural sources and sinks over land (CO_2 land) using bottom-up (BU) and top-down (TD) approaches for the European Union (EU27), updating earlier syntheses (Petrescu et al., 2020, 2021b; McGrath et al., 2023). Given the wide scope of the work and the variety of approaches involved, this study aims to answer essential questions identified in the previous syntheses and understand the differences between datasets, particularly for poorly characterized fluxes from managed ecosystems. The work integrates updated emission inventory data, process-based model results, data-driven sectoral model results, and inverse modeling estimates, covering the period 1990-2021 to the extent possible. BU and TD products are compared with European National Greenhouse Gas Inventories (NGHGIs) reported by Parties including the year 2021 under the United Nations Framework Convention on Climate Change (UNFCCC). The uncertainties of the EU27 NGHGI were evaluated using the standard deviation reported by the EU Member States following the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and harmonized by gap-filling procedures. Variation in estimates produced with other methods, such as atmospheric inversion models (TD) or spatially disaggregated inventory datasets (BU), originate from within-model uncertainty related to parameterization as well as structural differences between models. By comparing NGHGIs with other approaches, key sources of differences between estimates arise primarily in activities. System boundaries and emission categories create differences in CO_2 fossil datasets, while different land use definitions for reporting emissions from Land Use, Land Use Change and Forestry (LULUCF) activities result in differences for CO_2 land.

For CO_2 fossil emissions, after harmonizing estimates based on common activities and selecting the most recent year available for all datasets (2019), the UNFCCC NGHGI for the EU27 accounts for 2920 ± 41 Tg CO_2 yr^{-1} (797 ± 11 Tg C yr^{-1}), while eight other BU sources report a median value of 2730 [2690,2750] [25th,75th percentile] Tg CO_2 yr^{-1} (744 [733,751] Tg C yr^{-1}). Two top-down inversions of fossil emissions currently available accounts for 3090 Tg CO_2 yr^{-1} (843 Tg C yr^{-1}) for the same year, a value close to that of the NGHGI, but for which uncertainty estimates are not yet available. **For the net CO_2 land fluxes,** during the only period where all datasets overlap (2015-2018), the NGHGI accounted for -80 [± 28 Tg C yr^{-1} while seven other BU approaches reported a mean sink of -59 [-103,-38] Tg C yr^{-1} and a 18-member ensemble of dynamic global vegetation models (DGVMs) reported -93 [-183,-34] Tg C yr^{-1}. The mean of three TD regional ensembles combined with one non-ensemble inversion of -105 Tg C yr^{-1} over the same period has a slightly smaller spread (0th-100th percentile of [-197,-73] Tg C yr^{-1}), and was calculated after removing land-atmosphere CO_2 fluxes caused by lateral transport of carbon (crops, wood trade and inland waters) resulting in increased agreement with the the NGHGI and bottom-up approaches. Results at the sub-sector level (Forestland, Cropland, Grassland) show generally good agreement between the NGHGI and sub-sector-specific models, but results for a DGVM are mixed. Overall, for both CO_2 fossil and net CO_2 land fluxes, we find current independent approaches are consistent with the

NGHGI at the scale of the EU27. We conclude that CO_2 emissions from fossil sources have decreased over the past 30 years in the EU27, while large uncertainties on net uptake of CO_2 by the land surface prevent trend identification. In addition, a gap on the order of 1000 Tg C yr^{-1} between CO_2 fossil emissions and net CO_2 uptake by the land exists regardless of the type of approach (NGHGI, TD, BU), falling well outside all available estimates of uncertainties. However, uncertainties in top-down approaches to estimate CO_2 fossil emissions remain uncharacterized and are likely substantial. The data used to plot the figures are available at a dedicated web site (https://webportals.ipsl.fr/VERIFY/FactSheets/) where the synthesis plots for EU27 as well as for all individual countries are accessible.

2 Introduction

Atmospheric concentrations of greenhouse gases (GHGs) reflect a balance between emissions from both human activities and natural sources, and removals by the terrestrial biosphere, oceans, and atmospheric oxidation. Increasing levels of GHG in the atmosphere due to human activities have been the major driver of climate change since the pre-industrial period (IPCC, 2021). In 2020, GHG mole fractions reached record highs, with globally averaged mole fractions of 413.2 parts per million (ppm) for carbon dioxide (CO_2), representing 149% of the pre-industrial level (WMO, 2021). The rise in CO_2 concentrations in recent decades is caused primarily by CO_2 emissions from fossil sources. Globally, fossil emissions in 2021 (excluding the cement carbonation sink) totalled 10.1 ± 0.5 Gt C yr^{-1} (34.8 ± 1.8 Gt CO_2 yr^{-1}) (Friedlingstein et al., 2022). In contrast, global net CO_2 emissions from land use and land use change (LULUC, primarily deforestation) estimated from bookkeeping models and dynamic global vegetation models (DGVMs) were estimated to have a small decreasing trend over the past two decades, albeit with low confidence (Friedlingstein et al., 2022). This decrease, however, is almost an order of magnitude less than the growth in fossil emissions over the same period, and therefore the total fossil and net LULUC flux has still increased.

As all countries in the EU27 are Annex I Parties[1] to the United Nations Framework Convention on Climate Change (UNFCCC), they prepare and report national GHG emission inventories (NGHGIs) on an annual basis. These inventories contain annual time series of each country's GHG emissions from the 1990 base year[2] until two years before the year of reporting and were originally set to track progress towards their reduction targets under the Kyoto Protocol (UNFCCC, 1997). Annex I NGHGIs are reported according to the Decision 24/CP.19 of the UNFCCC Conference of the Parties (COP) which states that the national inventories shall be compiled using the methodologies provided in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The 2006 IPCC Guidelines provide methodological guidance for estimating emissions for well-defined sectors using national activity and available emission factors. Decision trees indicate the appropriate level of methodological sophistication (Tiered methods) based on the absolute contribution of the sector to the national GHG balance and the country's national circumstances (availability and resolution of national activity data and emission factors). Generally, Tier 1 methods are based on global or regional default emission factors that can be used with aggregated activity data, while Tier 2 methods rely on country-specific factors and/or activity data at a higher category resolution. Tier 3 methods are based on more detailed process-level modeling or in some cases facility-level emission observations. Annex I Parties are furthermore required to estimate and report uncertainties in emissions (95 % confidence interval) following the 2006 IPCC guidelines using, as a minimum requirement, the Gaussian error propagation method (approach 1). Annex I Parties are furthermore encouraged to use Monte-Carlo methods (approach 2) or a hybrid approach. Additional information on the NGHGIs can be found in Appendix.

In addition to the NGHGIs, other research groups and international institutions produce independent estimates of national GHG emissions with two approaches: atmospheric inversions (top-down, TD) and GHG inventories based on the same principle as NGHGIs but using slightly different methods (tiers), activity data, and/or emissions factors (bottom-up, BU). The current work has a strong focus on the EU27, and therefore sits within the context of recent legislation passed by the European Parliament concerning commitments for the LULUCF sector to achieve the objectives of the Paris Agreement and the reduction target for the Union (EU, 2018a and the proposed amendments, EU, 2021a). This legislation requires that, “Member States shall ensure that their accounts and other data provided under this Regulation are accurate, complete, consistent, comparable and transparent”. The TD and BU methods discussed below include the most up-to-date publicly available spatially explicit information, which can help provide a quality check and increase public confidence in NGHGIs.

The work presented in this paper covers dozens of distinct datasets and models, in addition to the individual country submissions to the UNFCCC of the EU Member States. As Annex I Parties, the NGHGIs of the EU Member States are consistent with the general guidance laid out in IPCC (2006) yet still differ in specific approaches, models, and parameters, in addition to definitional differences in the underlying system boundaries and activity datasets. A comprehensive investigation of detailed differences between all datasets is beyond the scope of this paper, though systematic analyses have been previously made for specific sectors (e.g. AFOLU[3] - Petrescu et al., 2020; previous synthesis to this work - Petrescu et al., 2021b, and McGrath et al., 2023; FAOSTAT versus UNFCCC NGHGIs - Tubiello et al., 2021, Grassi et al., 2022a; UNFCCC versus bookkeeping models - Grassi et al, 2023; and UNFCCC versus inversions - Deng et al., 2021) and by the Global Carbon Project CO_2 syntheses (e.g., Friedlingstein et al., 2022). Every year (time “t”) the Global Carbon Project (GCP) in its Global Carbon Budget (GCB) quantifies large-scale CO_2 budgets up to the previous year (“t-1”), bringing in information from global to large latitude bands, including various observation-based flux estimates from BU and TD approaches (Friedlingstein et al., 2022). The current manuscript, given the focus on a single region (“Europe") with extensive data coverage, dives into more detail than the GCB, including sector-specific models related to LULUCF (e.g., Forest land, Grassland, Cropland) and making heavy use of the EU27 NGHGI in an effort to build mutual trust in the various approaches. Compared to McGrath et al. (2023), the current work updates datasets, methods, and uncertainties and discusses a few country-level examples. A focus is on covering up to year 2021 as possible.

BU observation-based approaches used in the GCB rely heavily on statistical data combined with Tier 1 and Tier 2 approaches. In the current work, focusing on a region that is well-covered with data and models (EU27), BU also refers to Tier 3 process-based models (see Sect. 2). At regional and country scales, systematic and regular comparison of these observation-based CO_2 flux estimates with reported fluxes under the UNFCCC is more difficult. Continuing our previous efforts within the European project VERIFY (VERIFY, 2022), the current study compares observation-based flux estimates of BU versus TD approaches and compares them with NGHGI for the EU27 bloc, using updated flux estimates covering the year

2021 whenever possible. Using the VERIFY website, we also provide similar comparisons for all European countries (VERIFY-CoCO2 Synthesis Plots, 2023). The methodological and scientific challenges to compare these different estimates have been partly investigated before (Pongratz et al., 2021, Grassi et al., 2018a, for LULUCF; Andrew, 2020, for fossil sectors) but such comparisons were not done in a systematic and comprehensive way, including both fossil and land-based CO_2 fluxes, before Petrescu et al. (2021b).

McGrath et al. (2023) is the most comprehensive comparison of the NGHGI and research datasets (including both TD and BU approaches) for the EU27+UK to date. The current paper narrows the focus to the EU27, given the departure of the United Kingdom from the European Union, and improves estimates compared to the previous version. Official NGHGI emissions are compared with research datasets, including necessary harmonization of the latter on total emissions to ensure consistency. Differences and inconsistencies between emission estimates were analyzed, and recommendations were made towards future evaluation of NGHGI data. It is important to remember that, while NGHGIs include uncertainty estimates, the “uncertainty analysis should be seen, first and foremost, as a means to help prioritize national efforts to reduce the uncertainty of inventories in the future, and guide decisions on methodological choice” (Volume 1, Chapter 3, IPCC, 2006) and were therefore not developed to enable comparisons between countries or other datasets. In addition, individual spatially disaggregated research emission datasets often lack quantification of uncertainty. Here, we focus on the mean value and various percentiles (0th, 25th, 75th, 100th) of different research products of the same type to get a first estimate of uncertainty (see Sect. 2). Not all models/inventories provided an update for v2022, and, therefore, for the non-updated datasets the previously published time series are shown.

The dataset/analysis assembled in this paper will be further used in a scientific paper in the ESSD journal (submitted before the end of the CoCO2 project), as an update of the previous synthesis (McGrath et al., 2023). It provides annual values of carbon dioxide emissions and sinks in fossil and LULUCF sectors for the EU27 across a range of data products based on different methodologies. This work provides, for example, researchers producing datasets based on new methods with a source of evaluation in the form of a best-estimate range of values. Decision makers may also find the results useful for targeting mitigation efforts in the EU27 by providing a more complete sectorial breakdown. While NGHGIs already provide detailed data-based disaggregation based on activities, the dataset here adds additional constraints from independent data and models used outside of the inventory community. In addition, this paper outlines a methodology by which users of country-level CO_2 emission data can compare datasets against NGHGIs and identify where agreement occurs for the right (and wrong) reasons. Section 3 provides a description of the data sources, while section 4 provides the main results and discussion. In particular, section 4.2 highlights the extreme difference between current fossil emissions and uptake by the land surface; section 4.3 shows good agreement between top-down and bottom-up approaches for fossil emissions; section 4.4 shows that better agreement between NGHGIs and other models occurs when the models are driven strongly by sector-specific data in forestry, grasslands, and croplands, as opposed to more generalized models created to couple to atmospheric models in global climate projections. Section 4.5 highlights the challenges currently facing comparison of atmospheric inversion models with NGHGIs, while simultaneously showing improvement by accounting for lateral transfer of carbon between countries.

A list of acronyms and terminology is provided in Table 6.1.1 for easy reference.

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[1] Annex I Parties include the industrialized countries that were members of the OECD (Organization for Economic Co-operation and Development) in 1992 plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several central and eastern European states (UNFCCC, https://unfccc.int/parties-observers, last access: February 2022).

[2] For most Annex I Parties, the historical base year is 1990. However, parties included in Annex I with an economy in transition during the early 1990s (EIT Parties) were allowed to choose one year up to a few years before 1990 as reference because of a non-representative collapse during the breakup of the Soviet Union. For the EU27+UK, this includes Bulgaria (1988), Hungary (1985–1987), Poland (1988), Romania (1989), and Slovenia (1986).

[3] We refer here to AFOLU as defined by the IPCC AR5: Agriculture, Forestry and Other Land Use.

3 CO_2 data sources and estimation approaches

3.1 CO_2 anthropogenic emissions from NGHGI

The UNFCCC NGHGI (2022) estimates for the period 1990 to year t-2 (2020), collected for the EU27, are the basis for this dataset. Note that new estimates covering the year 2021 shall be released before the summer 2023; these updates will thus be used in the scientific paper associated with this deliverable (to be submitted at the end of 2023). For historical reasons, a few EU countries provide data for a different base year than 1990[1], yet it should be noted that regardless of the base year all countries of the EU27 bloc are obliged to report estimates for the period 1990 to year t-2. The Annex I Parties to the UNFCCC are required to report annual GHG inventories that include a NIR, with qualitative information on data and methods and a Common Reporting Format (CRF) set of tables that provide quantitative information on GHG emission by category. This annually updated dataset includes anthropogenic emissions and removals. For the land-based sector, the land management proxy is used as a way to report only anthropogenic fluxes (Grassi et al., 2018a, 2021). This proxy allows Member States to report all fluxes coming from land designed as “managed” without trying to disentangle their natural and anthropogenic origins.

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[1] For most Annex I Parties, the historical base year is 1990. However, parties included in Annex I with an economy in transition during the early 1990s (EIT Parties) were allowed to choose one year up to a few years before 1990 as reference because of a non-representative collapse during the breakup of the Soviet Union (e.g., Bulgaria, 1988, Hungary, 1985–1987, Poland, 1988, Romania, 1989, and Slovenia, 1986).

3.2 CO_2 fossil emissions

Table 1: Data sources for the anthropogenic CO_2 fossil emissions included in this study, all updated from McGrath et al. (2023):

Anthropogenic CO_2 fossil			
Data/model name	**Contact / lab**	**Species / Period**	**Reference/Metadata**
UNFCCC NGHGI (2023)	UNFCCC	Anthropogenic fossil CO_2 1990-2021	IPCC (2006) UNFCCC NIRs/CRFs https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2023 (UNFCCC, 2023)
Compilation of multiple CO_2 fossil emission data sources (Andrew 2020) EDGAR, BP, EIA, CDIAC, IEA, GCP, CEDS, PRIMAP	CICERO	CO_2 fossil country totals and split by fuel type 1990-2021 (or last available year)	EDGAR v7.0 https://edgar.jrc.ec.europa.eu/ BP 2022 report (BP, 2022) EIA as at 24 December 2022 https://www.eia.gov/beta/international/data/browser/views/partials/sources.html CDIAC 2022 https://energy.appstate.edu/CDIAC (Gilfillan and Marland, 2021) IEA August 2022 edition : www.iea.org CEDS 2021_04_21 https://github.com/JGCRI/CEDS (O'Rourke et al., 2021) GCB 2022 (Friedlingstein et al., 2022) PRIMAP-hist 2.4.2 (Gütschow et al., 2021) https://doi.org/10.5281/zenodo.4479171
Fossil fuel CO_2 inversions	LSCE	Inverse fossil fuel CO_2 emissions 2005-2020	Fortems-Cheiney et al. (2021) Fortems-Cheiney and Broquet (2021)

3.3 CO_2 land fluxes

Table 2: Data sources for the land CO_2 emissions included in this study. Details are found in Appendix A2.

NGHGI net CO_2 land flux				
Data source	**Contact / lab**	**Variables Period (timestep) Resolution**	**References**	**Status compared to McGrath et al. (2023)**
UNFCCC NGHGI (2022)	Member State inventory agencies Annual uncertainty gap-filling for total LULUCF by Environment Agency Austria (EAA).	LULUCF Net CO_2 emissions/removals. 1990-2020 (1Y) Country-level	IPCC (2006) UNFCCC CRFs https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019	Updated
Inventory and model estimates of net CO_2 land flux				
ORCHIDEE	LSCE	CO_2 fluxes from all ecosystems reported as Net Biome Productivity (NBP). Model includes N cycling. 1990-2021 (3H) 0.125° x 0.125°	Ducoudré et al. (1993) Viovy et al. (1996) Polcher et al. (1998) Krinner et al. (2005) Vuichard et al. (2019)	Updated
CABLE-POP	Western Sydney University	CO_2 fluxes (NBP). Model includes N cycling. 1990-2020 (1M); 0.125° x 0.125°	Haverd et al. (2018)	Not updated
LPX-BERN	UBern	CO_2 fluxes (NBP). Model includes N cycling. 1990-2021 (1M) 0.125° x 0.125°	Lienert et. al. (2018) Joos et al. (2020)	New
TRENDY v11	MetOffice UK	CO_2 fluxes (NBP) 18 models 1990-2021 (3H-1M); Various spatial resolutions	Friedlingstein et al. (2022; Table 4)	Updated

CO_2 emissions from lateral transfer of carbon	LSCE	Average C fluxes from rivers, lakes and reservoirs, with lateral C transfer from soils, and emissions from crop and wood trade.. 1990-2021 (1M) 0.5° x 0.5°	Lauerwald et al. (2015) Hastie et al. (2019) Raymond et al. (2013)	Updated
CBM	EC-JRC	CO_2 fluxes (NBP) as historical 2000-2015 and extrapolation for 2017-2020 (1Y) Country-level	Kurz et al. (2009) Pilli et al. (2022)	Not updated
ECOSSE	UNIABDN	CO_2 fluxes (NBP) from croplands and grassland ecosystems. Crops: 1990-2020 (1Y) Grass: 1990-2018 (1Y) 0.125° x 0.125°	Bradbury et al. (1993) Coleman (1996) Jenkinson (1977, 1987) Smith et al. (1996, 2010a,b)	Not updated
EFISCEN-Space	WUR	CO_2 fluxes (NBP): single average value for 5 year periods, replicated on a yearly time axis. 0.125° x 0.125°	Verkerk et al. (2016) Schelhaas et al. (2017, 2020) Nabuurs et al. (2018)	Not updated
EPIC-IIASA	IIASA	CO_2 fluxes (NBP) from cropland 1991-2021 (1M) 0.125° x 0.125°	Balkovič et al. (2013, 2018, 2020) Izaurralde et al. (2006) Williams et al. (1990)	Updated for both croplands and grasslands
BLUE (VERIFY) and BLUE (GCP)	LMU Munich	CO_2 fluxes from land use change. VERIFY: 1990-2019 (1Y) GCP: 1990-2020 (1Y) 0.25° x 0.25°	Hansis et al. (2015) Ganzenmüller et al. (2022) - VERIFY Friedlingstein et al. (2022) - GCP2021	Not updated
H&N	Woodwell Climate Research Center	CO_2 fluxes from land use change. 1990-2020 (1Y) Country-level	Houghton and Nassikas (2017)	Not updated
FAO	FAOSTAT	CO_2 emissions / removal from LULUCF processes. 1990-2020 (1Y) Country-level	FAO (2021) Federici et al. (2015) Tubiello et al. (2021)	Updated
CO_2 atmospheric inversion estimates				
CSR inversions for VERIFY	MPI -Jena	Total CO_2 inverse flux (NBP) 2006-2021 (3H) 0.5° x 0.5°	Kountouris et al. (2018 a,b)	Updated

LUMIA	Lund University (INES)	Total CO_2 inverse flux (NBP) 2006-2020 (1W) 0.25° x 0.25°	Monteil and Scholze (2021)	Not updated
CIF-CHIMERE	LSCE	Total CO_2 inverse flux (NBP) 2005-2020 (3H) 0.5° x 0.5°	Berchet et al. (2021) Broquet et al. (2013)	Not updated
GCP 2022 global inversions (CAMS, CAMS-Satellite, CTE, GONGGA, JENA-sEXT, NIES-NIWA, UoE)	GCP	Total CO_2 inverse flux (NBP) Six inversions 2015-2021 (various)	Friedlingstein et al. (2022) Van der Laan-Luijk et al. (2017) Chevallier et al. (2005) Rödenbeck et al. (2005) Niwa et al. (2017) Feng et al. (2016) Liu et al. (2021)	Updated . CMS-Flux was not included as the one-degree maps have not been properly processed by the GCP team. THU was removed as it shows an abnormally strong sink.
EUROCOM regional inversions (CSR, LUMIA, PYVAR)	LSCE, ULUND, MPI-Jena, NILU	Total CO_2 inverse flux (NBP) Three inversions 2009-2018 (3H-1M)	Monteil et al. (2020) Thompson et al. (2020)	Not updated

4 Results and discussion

4.1 Access to all country and groups of countries synthesis plots

Before presenting the results (primarily for the EU27), we describe in this section how to access the different flux synthesis plots for all countries and groups of countries from a dedicated web-site. The site was designed during the VERIFY project and further extended in CoCO2 in order to include the updated synthesis plots produced in 2022: https://webportals.ipsl.fr/VERIFY/FactSheets/. This page of the website proposes several options and menus:

- On the left an interactive map allows one to select individual countries with a menu to select predefined groups of countries.
- The upper right menu allows one to select different types of plots. For this particular deliverable, we focus on two groups: “Synthesis CO2land” and “Synthesis CO2fossil”. For each group one can select a particular type of plot or all plots.
- On the right below the plot selection menu, one can finally select to view the synthesis plots by clicking on “Display plots”.

Note that there are also other options on this page (not used in this particular deliverable) to display “all comments provided about individual plots” and more importantly to display summary factsheets for all selected regions (“Display national inventory factsheets” and “Display observation-based summary factsheets”) that were used in the previous deliverable D6.1.

Once the “Display plots” is selected a new page is opened providing a mosaic gathering all selected plots for all selected regions (countries and groups of countries). From this new page, double clicking on a given plot enlarges it as shown in figure 1 below (right panel). The enlarged figure provides several options across the top headband, as illustrated in figure 1:

- A menu to select the different versions of the plot (V2019, V2020, V2021 and V2022, in the example below), with the most recent version being selected by default. Note that for some plots, only the version V2022 is available or only up to V2021.
- A menu to download the data set used to create the plot (as a “cvs” file).
- Two arrow buttons to change plots if the initial selection contains several types of plot and or several regions (as it is the case in figure 1 with the mosaic of plots on the left panel).
- Two options (“i” and “?”) to get specific information including the legend and the caption of the plot.

Importantly the left panel of figure 1 (first display of all selected plots) is uniquely referenced by its web URL (Uniform Resource Locator), which thus allows sharing a unique link to any specific plot. We use this facility in the sections below to provide additional examples of synthesis plots for individual countries (the deliverable provides illustration only for EU27), without overloading the document with a large number of figures.

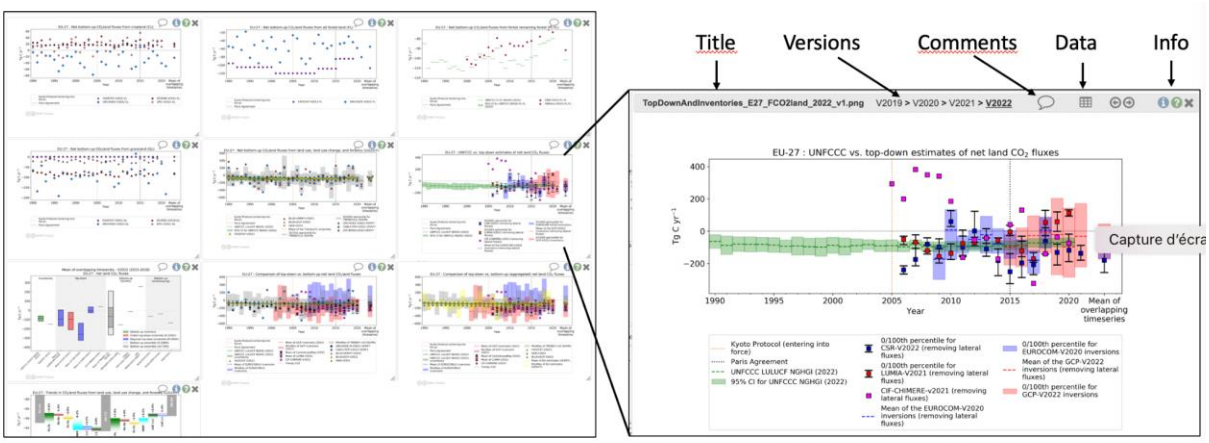

Figure 1: Illustration of the website facility to visualise all synthesis plots for an ensemble of regions (countries or groups of countries). The left panel shows the mosaic of plots produced once the different regions and types of plots have been selected. The right figure illustrates the result of enlarging one plot of the selected ensemble (by double clicking) with options to change the version, add comments, obtain the data associated with the plot and obtain information about the plot (caption, legend).

4.2 Overall NGHGI reported anthropogenic CO_2 fluxes

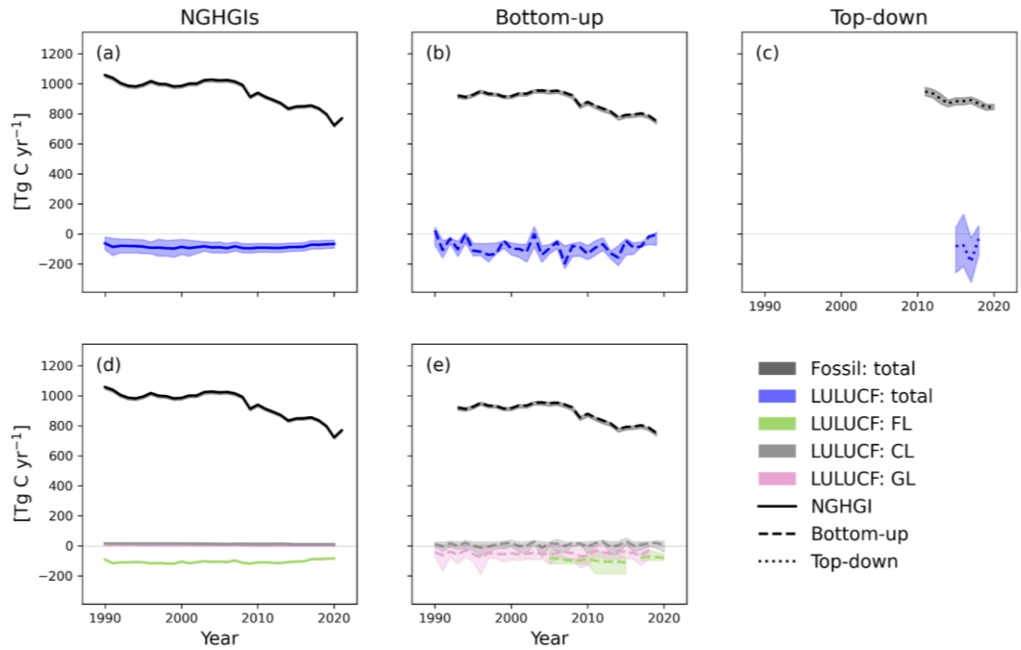

Figure 2: A synthesis of all the CO_2 net fluxes shown in the work for the EU27. The estimates are divided by approach: NGHGI estimates (panels a, d); bottom-up methods (b, e); and top-down methods (c). Panels (d) and (e) include a breakdown of the LULUCF flux into three of the dominant components: FL, GL, and CL. Such a breakdown is not provided for NHGHI CO2 fossil as partitioning of bottom-up CO_2 fossil datasets corresponding to UNFCCC NGHGI categories is not currently available. The NGHGI UNFCCC uncertainty is calculated for submission year 2022 as the relative error of the NGHGI value, computed with the 95 % confidence interval method gap-filled and provided for every year of the timeseries; no uncertainties are provided for FL, CL, and GL. Shaded areas for the other estimates represent the 0th-100th percentiles for groups with fewer than seven members, and the 25th-75th percentile for groups with seven or more members. Ensembles (e.g., TRENDY v11) are included in the above only as their mean values, to avoid more heavily weighting the ensembles compared to the other datasets.

Two major conclusions are supported by Fig. 2. First, there is a large difference between the emissions of fossil CO_2 and the amount of CO_2 uptake by the land sink in the European Union. This difference is almost one order of magnitude, and exists regardless of the type of method (NGHGI, bottom-up, or top-down) and the estimated uncertainties. Second, the uncertainties and interannual fluctuations are much higher in the LULUCF fluxes than the fossil emissions.

Several caveats remain with this overall synthesis. First, the timeseries were combined rather naively in Fig. 2 by taking the mean of annual timeseries for each dataset discussed below. This leads to, for example, the 18-member TRENDY ensemble being given identical weight as the ORCHIDEE high-resolution simulation over Europe. This was done to weigh more heavily the regional approaches under the assumption that higher resolution simulations and more region-specific input data will lead to more accurate results. While the latter assumption appears reasonable, the first assumption can be disputed. Second, only two top-down results for fossil CO_2 emissions are currently available, preventing a robust estimate of the uncertainty for this approach. Third, sector models were combined disregarding distinctions between those models estimating "Remain" and "Total" fluxes. These points are discussed in more detail in the following sections. However, addressing these points is highly unlikely to alter the overall conclusions in this section.

Finally, a similar synthesis of all the net fluxes for each individual country in Europe is accessible from a dedicated website (see section 4.1). All plots are accessible with the following link: https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE&selectFCO2fossil=SummaryTimeseries
The two main conclusions above are generally applicable for all countries, with a few exceptions (for example, the uncertainty in fluxes "Forestland remaining forestland" for Austria leads to possible overlap with the fossil emissions).

4.3 CO_2 fossil emissions

The inventory-based fossil CO_2 estimates from nine data sources (and some subsets) are presented as timeseries (1990-last available year) based on Andrew (2020) with the objective to explore differences between datasets and visualize trends (Fig. 3). Because the emissions source coverage (also called the "system boundary") of datasets varies, comparing total emissions from these datasets is not a like-for-like comparison. Therefore, some harmonization of system boundaries prior to comparison is needed. This harmonization relies on specifying the system boundary of each dataset and, where possible, removing emission sources to produce a near-common system boundary. For example, if IEA doesn't include any carbonates, then carbonates are removed from all emissions datasets that report these separately. CDIAC, CEDS, PRIMAP, and GCP include Energy sector plus all fossil fuels in IPPU; EIA, EDGAR and BP include some fossil fuels in IPPU, while EIA and BP include bunker fuels as well. UNFCCC (CRFs) include Energy total and Total. Further details on how data sets are harmonized are provided by Andrew (2020). Because of differing levels of detail provided by datasets, it isn't possible to do this perfectly, but the approximate harmonization gives something closer to a like-for-like comparison, with the legend in Fig. 3 indicating the most significant remaining differences.

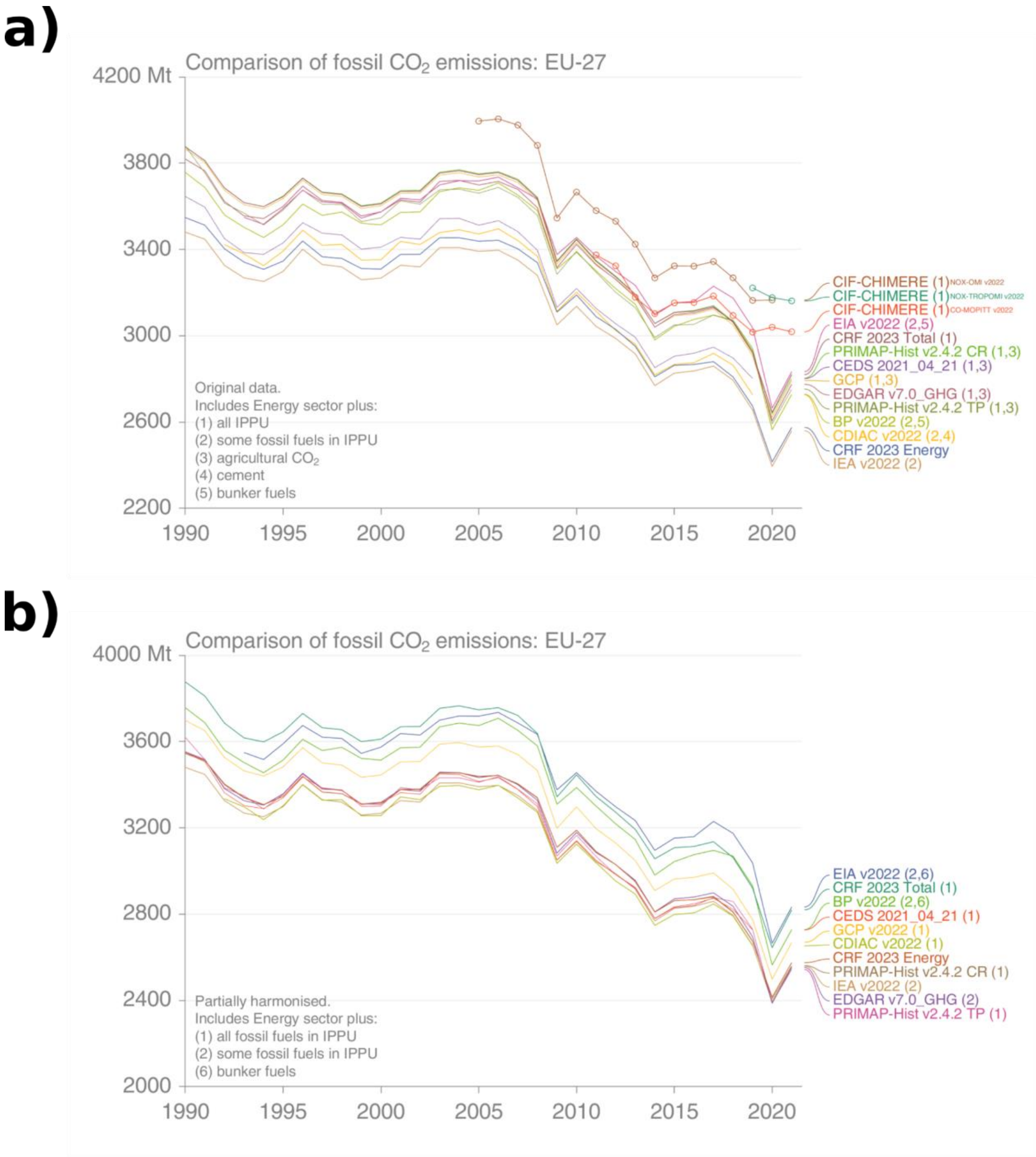

Figure 3: Comparison of EU27 fossil CO_2 emissions from multiple inventory datasets for the raw timeseries (a) and with system boundaries harmonized as much as possible (b). Harmonization is limited by the disaggregated information presented by each dataset. CDIAC does not report emissions prior to 1992 for former-Soviet Union countries. CRF: UNFCCC NGHGI from the Common Reporting Format tables. Results from atmospheric inversions are shown in (a).

Given the remaining differences in system boundaries after harmonization, most datasets agree well (Andrew, 2020). For comparison, applying a similar harmonization procedure to the UNFCCC NGHGI and retaining only Fuel combustion (1A), Fugitive emissions (1B), Mineral Industry (2A), Chemical industry (2B), Metal industry (2C), Non-energy products from fuels and solvent use (2D), and Other (2H) results in emissions of 2920 ± 41 Tg CO_2 yr^{-1} (797 ± 11 Tg C yr^{-1}) for the year 2019, where the uncertainty is 1.4%, using the same value from McGrath et al. (2023). This mean value is higher than the 25th-75th percentiles of the eight other harmonized BU sources ([2690,2750] Tg CO_2 yr^{-1}). The reason for this is that the total UNFCC numbers include Mineral Industry (2A), which is a non-fuel use and covers activities like cement, lime, and glass production, while the other BU approaches only report CO_2 emissions from fuel use. If only energy emissions in the UNFCC results are considered (CRF 2023 Energy in Fig. 3), and the same 1.4% uncertainty estimation is applied, the values become 2674 ± 37 Tg CO_2 yr-1 (730 ± 10 Tg C yr-1), the uncertainty interval of which overlaps with the 25th-75th percentile of the BU ensemble.

Fig. 3 shows two dramatic dips followed by rebounds in fossil CO_2 emissions in the European Union, one occurring in 2008 and another occurring in 2020. The first of these years corresponds to a global financial crisis, while the second corresponds to the beginning of the Covid-19 pandemic in which consumer behaviours changed dramatically. In both cases, emissions rebounded in the following year, although the 2021 rebound is more dramatic both in terms of relative and absolute values. In neither case, however, do the rebounds cancel the general tendency of emission reduction over the past decade. From this new synthesis we clearly see that 2021, the reference year for the first global stocktake, has to be put in the context of a post Covid-19 pandemics rebound.

The sole available inversions for CO_2 fossil fluxes are produced by the CIF-CHIMERE model, shown in Figs. 2c and 3a. The inversion yields plausible and consistent fossil emission estimates compared to nine bottom-up estimates from BU datasets with global coverage. Uncertainties of CIF-CHIMERE inversion estimate have not yet been quantified, however they are likely largely driven by large uncertainties in the observations and in the atmospheric chemistry and transport modelling. The satellite observations of NO_2 and CO have large uncertainties, which partly explains the small departure from the prior fluxes during the optimization. Emission ratios between NO_2 or CO and CO_2 are also uncertain (those from the prior are currently used). The atmospheric residence time of NO_2 is another major source of uncertainty. The inversion reports total fossil CO_2 emissions calculated from NOx or CO combustion emissions. However, in principle, the derivation of CO_2 emissions from the NOx or CO inversions should be restricted to fossil fuel CO_2 emissions based on the fossil fuel CO_2/NOx or CO_2/CO ratios from the TNO inventory, as there is a better-established relationship between CO_2 and NOx from combustion of fossil fuels. Future inversions co-assimilating CO_2 data will make a clearer distinction in the processing of fossil-fuel and other anthropogenic emissions. Furthermore, it's important to note that the inversion results are not fully independent of the bottom-up methods, as the prior estimates are based on TNO gridded products. However, these differences are relatively small at national and monthly scales, and part of the lack of departure from the prior can be attributed to the general consistency between the prior and the observations, which raise optimistic perspectives for the co-assimilation of co-emitted species with the data from future CO_2 networks dedicated to anthropogenic emissions.

Finally, the same time series for all individual EU countries are also available from the following link:

https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE&selectFCO2fossil=TotalFossilTimeseries

The same rebound for 2021 is present for most countries, although the magnitude is lower in countries like Denmark, Finland, and Greece. Emissions do not rebound in Portugal, Slovenia, and Sweden. This may be due to northern countries emitting more carbon dioxide in residential heating, the demand for which was not reduced by lockdowns, while countries with weaker economies may not have recovered as quickly from the drop, thus delaying the rebound of emissions. Note that the inversions show strange results for some countries, such as Turkey, due to boundary issues: the regional inversions are restricted to a rectangular region which did not include all of Turkey.

4.4 CO_2 land fluxes

This section updates the data collection of CO_2 emissions and removals from the LULUCF sector in EU27+UK previously published in McGrath et al. (2023), expanding on the scope of those works by adding additional datasets and years and narrowing the focus to the EU27. The countries analysed in this study use country-specific activity data and emissions factors for the most important land use categories and pools (EU NIR 2022). However, several gaps still exist, mainly in non-forest lands and non-biomass pools (e.g., EU NIR, 2022). In addition, since NGHGIs largely rely on periodic forest inventories (carried out every five to ten years) for the most important land use (Forest land), the net CO_2 LULUCF flux often does not capture the most recent changes, nor the full interannual variability.

While the net LULUCF CO_2 flux was relatively stable from 1990 to 2016, staying mostly between -80 to -100 Tg C/yr, in the past three years the sink has weakened to around -70 Tg C/yr in 2020 (e.g., Fig. 9). This weakening occurred mostly in Forest land, due to a combination of increased natural disturbances, forest aging and increased wood demand (Nabuurs et al., 2013; EU NIR, 2022). Natural disturbances, including fires (especially in the southern Mediterranean), windthrows, droughts and insect infestations (especially in central and northern European countries), have increased in recent years (e.g., Seidl et al., 2014) which explains most of the interannual variability of NGHGIs. Forest aging affects the net sink both through the forest growth (net increment) - which tends to level off or decline after a certain age - and the harvest, because a greater area of forest reaches forest maturity (Grassi et al., 2018b). Although the exact increase in total harvest in Europe in recent years is still subject to debate (Ceccherini et al., 2020; Palahi et al. et al., 2021), demand for fuelwood at least has increased (Camia et al., 2021). Official NGHGI results for the year 2021 are not yet available (they will be included in the final version of the article).

Carbon uptake as seen by the atmosphere may occur on either managed or unmanaged land, and results from processes such as photosynthesis, respiration, and disturbances (e.g., fire, pests, harvest). As discussed by Petrescu et al. (2020), the fluxes reported in NGHGIs relate to emissions and removals from direct LULUCF activities (clearing of vegetation for agricultural purposes, regrowth after agricultural abandonment, wood harvesting and recovery after harvest and management) but also indirect CO_2 fluxes due to processes such as responses to environmental drivers on managed land. Additional CO_2 fluxes occur on unmanaged land, but these fluxes are very small in Europe (see, for example, McGrath et al. (2023)).

The indirect CO_2 fluxes on managed and unmanaged land due to changing climate, increasing atmospheric carbon dioxide concentrations, and nitrogen deposition, are part of the (natural) land sink in the definition used in IPCC Assessment Reports and the Global Carbon Project's annual global carbon budget (Friedlingstein et al., 2022), while the direct LULUCF fluxes are termed "net land-use change flux", as discussed by Grassi et al. (2018a, 2021, 2022a), McGrath et al. (2023), Petrescu et al. (2020, 2021b) and Pongratz et al. (2021). Results should thus be interpreted with caution due to these definitional differences, but as most of the land in Europe is managed and the indirect effects are small, the definitional differences should be modest compared to other sources of uncertainty (Petrescu et al., 2020). Other relatively recent studies have already analyzed the European land carbon budget using GHG budgets from fluxes, inventories and inversions (Luyssaert et al., 2012) and from forest inventories (Pilli et al., 2017; Nabuurs et al., 2018).

4.4.1 Estimates of CO_2 land fluxes from bottom-up approaches

In this section we present annual total net CO_2 land emissions between 1990-2021 i.e., induced by both LULUCF and natural processes (e.g. environmental changes) from class-specific models as well as from models that simulate multiple land cover/land use classes. The definitions of the classes may differ from the IPCC definitions of LULUCF (e.g., FL, CL, GL) where, according to IPCC 2006 guidelines, to become accountable in the NGHGI under "remaining" categories, a land-use type must be in that class for at least N years (where N is the length of the transition period; 20 years by default). In an effort to create the most accurate comparison as possible in terms of categories and processes included, total Forest land (FL) has been divided up into Forest land remaining forest land (FL-FL) and Land converted to forest land (X-FL), while only total Grassland (GL) and Cropland (CL) are reported. This is largely due to the non-forest sector models explored here only considering net land use change, which prevents separating out the "converted" component.

Both Petrescu et al. (2021b) and McGrath et al. (2023) report uncertainty estimates for CO_2 land subsectors, such as Forest land remaining forest land (FL-FL). Such results are not official estimates included in the NIR for the EU, but rather calculated through standard error propagation techniques. In this work, we only include estimates of uncertainty where such estimates are reported or calculated by official representatives of the respective Member States. This means, for example, that uncertainty estimates are not given for the EU27 for LULUCF categories. In addition, reporting for the European Union includes the United Kingdom for years up to and including 2020 (EU, 2022), and therefore values from the UK must be removed from those reported by the EU in order to give results for the EU27.

Forest land

Fluxes from Forest land which remain in this class (FL-FL) are shown in Fig. 4. These fluxes were simulated with ecosystem models (CBM and EFISCEN-Space, described in more detail in the Appendices) and countries' official inventory statistics reported to UNFCCC. The results show that the differences between models are systematic, with CBM having slightly weaker sinks than EFISCEN-Space. CBM updated its historical data (1990-2015) and presents new NBP estimates based on extrapolation of historical timeseries (see Appendix) for 2017-2020 (CBMsim). Both CBM and EFISCEN-Space use national forest inventory (NFI) data as the main source of input to describe the current structure and composition of European forests. NFIs are also the main source of input data for most countries in the EU27 for NGHGIs (EU NIR, 2021), including data for carbon stock changes in various pools as well as the estimation of forest areas. EFISCEN-Space does not include results for the United Kingdom.

We therefore scale the EU27+UK results from McGrath et al. (2023) by 0.9904 (the ratio of the annual means for EU27 and EU27+UK from the EFISCEN dataset used in Petrscu et al. (2021b). As noted above, EU regulations are driving Member States to report spatially explicit NGHGIs. Unlike the original EFISCEN, EFISCEN-Space is a spatially explicit model, in addition to being able to simulate a wider variety of stand structures, species mixtures and management options. Note that EFISCEN-Space reports only a single mean value for forest fluxes from 2005-2020; the annually varying value shown in Fig. 4 arises from scaling by annually varying forest areas.

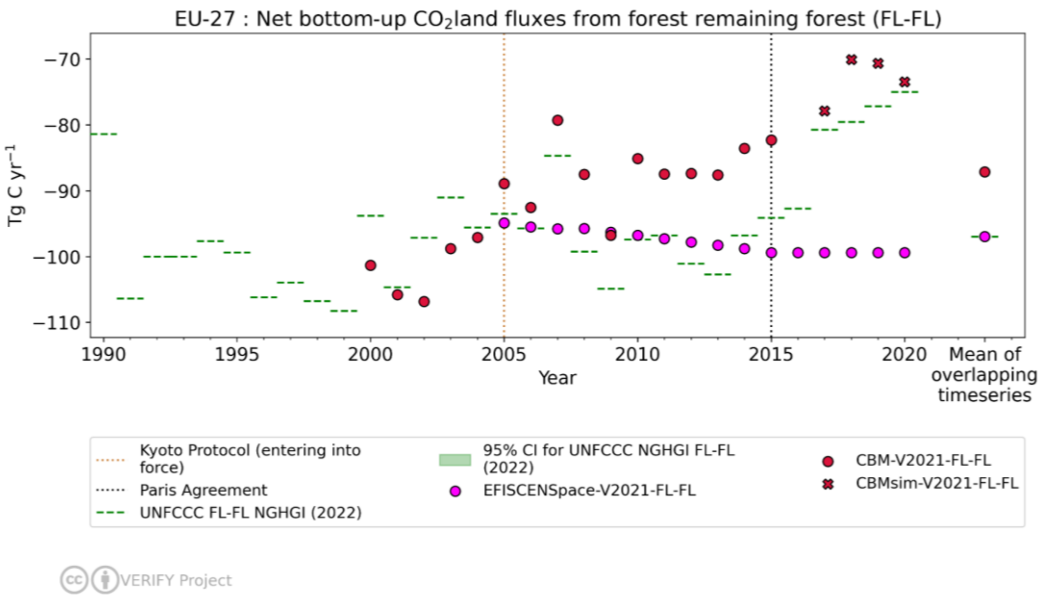

Figure 4: Net CO_2 land flux from Forest land remaining forest land (FL-FL) estimates for EU27. Means are given for 2005-2015 on the right side of both plots. CBM FL-FL historical estimates include 25 EU countries (excl. Cyprus and Malta) and include new estimates for 2017-2020 (red crosses). The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source. Notice that some timeseries have been removed and placed in Fig. 5 as some datasets more accurately depict fluxes from total Forest land (FL).

The UNFCCC NGHGI uncertainty of CO_2 estimates for FL-FL across the EU27 is not provided by the European Union, and we have not attempted to recalculate it here for reasons mentioned above. Despite contrasting methodologies and input data for emission calculation and uncertainties in each method (Appendix), there is reasonable agreement on the trend in FL-FL fluxes from CBMsim and the UNFCCC NGHGI (2021) (Fig. 4). The magnitude of the values between EFISCEN-Space and the NGHGI (2021) also agree well, though as noted above the EFISCEN-Space results only vary with the amount of forest area which makes the trend much flatter. Given that all three methods (NGHGI, CBM, and EFISCEN-Space) are heavily based on national forest inventory data, the general agreement between the three is not surprising.

The same time series for all individual EU countries are also available from the following link:

https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=ForestRemain

Similar results are found at the country scale with systematic differences between models but not always of the same sign between CBM and EFISCEN-Space.

Figure 5 presents CO_2 land estimates for total Forest land (both remain and convert classes, "FL"). For the total Forest land, the results were simulated with an ecosystem model (ORCHIDEE) and a global dataset (FAOSTAT) as it is not possible for these two approaches to separate out the "remain" and "convert" land use category. This obstacle arises due to the use of net land use/land cover information which does not include detailed information on the nature of the conversions. Consequently, Fig. 5 compares them to the total Forest land from the countries' official inventory statistics (UNFCCC NGHGI, 2022).

From 2001 and until 2010, the FAOSTAT reports an increasing sink over time, which weakens from 2011 until 2019 (Fig. 5). Unlike the FAOSTAT data from McGrath et al. (2023), Romanian estimates for Forestland and Net forest conversion have been included in this analysis. Starting in 2016, FAOSTAT estimates better match those from the NGHGIs as FAOSTAT updated its estimates. FAOSTAT uses input data directly from country submissions to the FAO Global Forest Resource Assessments (FRA[6]) (e.g., carbon stock change is calculated by FAO directly from carbon stocks and area data submitted by countries). It is important to note that these data are not always identical to those submitted to the UNFCCC (Tubiello et al., 2021).

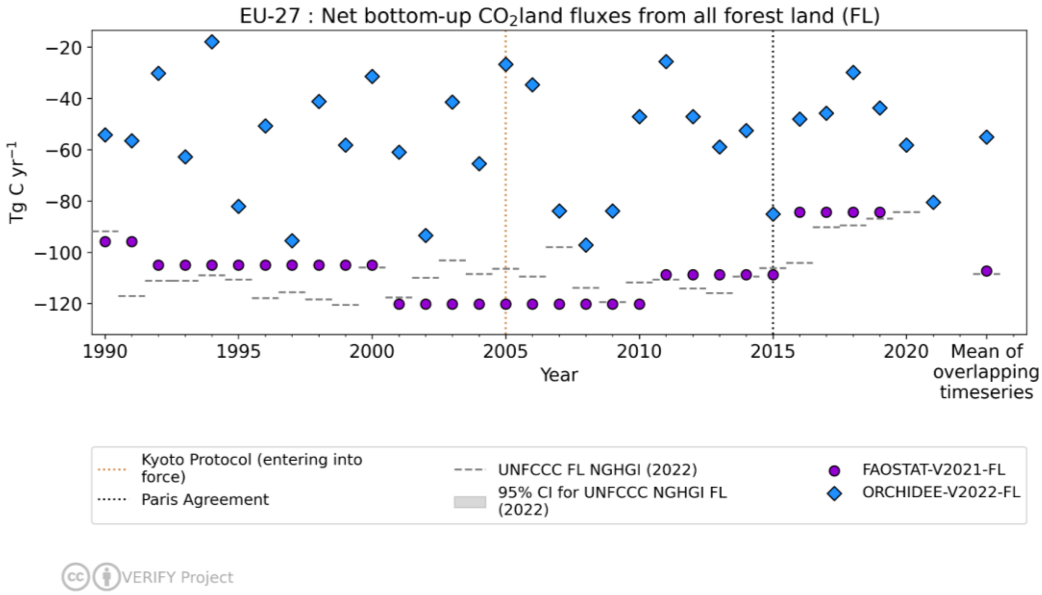

Figure 5: Net CO_2 land flux from total Forest land estimates (FL) for EU27 CO_2 from the UNFCCC NGHGI (2022) submissions, the FAOSTAT data-driven inventory, and the ORCHIDEE DGVM. The means are calculated for the 1990–2019 overlapping period. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

[6] The Global Forest Resource Assessment (*FRA*) is the supplementary source of Forest land data disseminated in *FAOSTAT*, http://www.FAO.org/forestry/fra/en/

The year 2021 shows a stronger-than-normal sink in the forest land in the European Union, although such a datapoint is only available for a single model in Fig. 5. Reasons for inter-annual-variability in ORCHIDEE remain identical to those given in McGrath et al. (2023), which are primarily use of sub-daily meteorolgoical forcing versus other methods based on multi-year forest inventories in other methods. Explanations for the dIfferences between the estimates in Figs. 4 and 5 are also identical to that reported in McGrath et al. (2023), and include classification of shrubland, inclusion of management into the model, and uncertainties in input data.

The same time series for all individual EU countries are also available from the following link:

https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=Forest

Although each country has slightly different inter-annual forest sink variations, similar increases of the sink in 2021 compared to 2020 is simulated by the ORCHIDEE model for most countries, except a few (Finland, Romania, Portugal, Italy and Greece).

Cropland

Total Cropland (CL, represented in the UNFCCC NGHGI 2022 as UNFCCC category 4B) includes net CO_2 emissions and removals from soil organic carbon (SOC) under “remaining” and “conversion” categories. Figure 6 shows the annual fluxes belonging to the category CL from the NGHGI for the EU27 along with four other approaches: one bottom-up inventory (FAOSTAT), two sector-specific models (EPIC-IIASA, ECOSSE), and one DGVM (ORCHIDEE). Note that the FAOSTAT value only includes the carbon flux from organic soils drained for agriculture, while ECOSSE, EPIC-IIASA, and ORCHIDEE include biomass volatilized immediately upon harvest; biomass left on site to decay as litter; and soil organic carbon.

For the common period (1990-2020), ORCHIDEE simulates a mean sink of -24 Tg C yr^{-1}, while ECOSSE, EPIC-IIASA, and FAOSTAT all simulate mean sources of 22 Tg C yr^{-1}, 8 Tg C yr^{-1} and 26 Tg C yr^{-1}, respectively. EPIC-IIASA has the best agreement with the NGHGI results (mean over the same period of 13 Tg C yr^{-1}). For all four bottom-up models, the mean from 1990-2020 is 12.8 Tg C yr^{-1}, with a 25-75th percentile overlapping zero. Results for 2021 follow the patterns of the rest of the timeseries: a strong sink for ORCHIDEE, and a source for EPIC-IIASA, with no data yet available from other approaches. Explanations for the differences in Fig. 6 remain identical to those given in McGrath et al. (2023), including injection of harvest residues into the soil, reporting of drained organic soils, year-to-year variability due to meteorology, and definitions of croplands. For the latter, the interested reader is referred to tables 6.10 (forests), 6.18 (croplands), and 6.22 (grassland) in the 2022 NIR of the European Union (EEA/PUBL/2022/023).

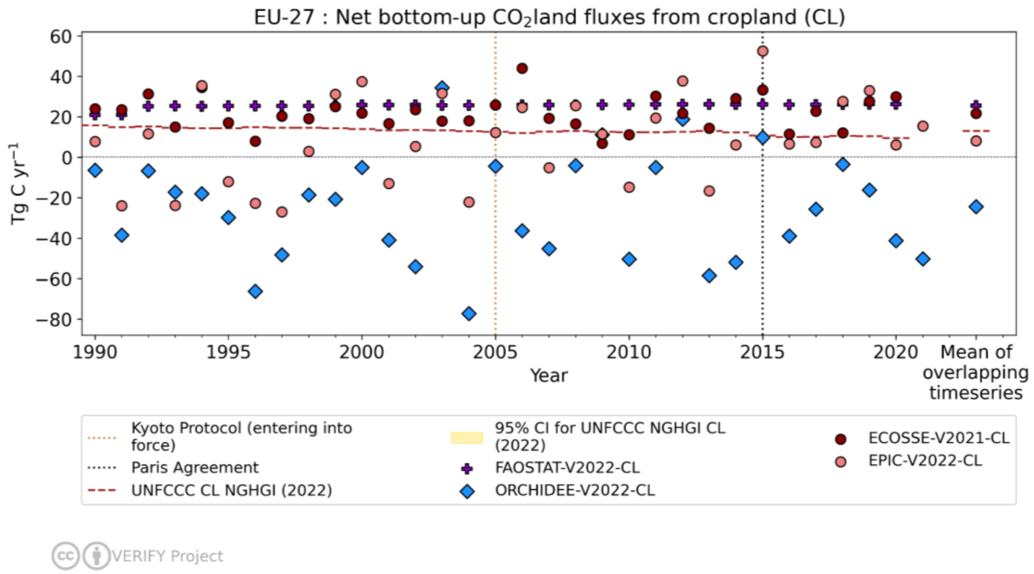

Figure 6: Net CO_2 land flux from Cropland estimates for the EU27 from the UNFCCC NGHGI (2022) submissions and models showing net carbon fluxes for the total Cropland (CL), with their 1990-2020 mean given on the right. CL net carbon fluxes are estimated with three ecosystem models: ORCHIDEE, ECOSSE and EPIC-IIASA, in addition to the FAOSTAT inventory. Note that the FAOSTAT value only includes the carbon flux from organic soils drained for agriculture. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

The same time series for all individual EU countries are also available from the following link:

https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=CroplandRemain

For nearly all countries ORCHIDEE simulates a mean sink (except for Finland, Estonia and Romania) while the other estimates simulate on average a mean source (except ECOSSE for Portugal). These country specific differences are under investigation.

Grassland

Grassland (GL, UNFCCC category 4C) includes net CO_2 emissions and removals from soil organic carbon (SOC) under “remaining” and “conversion” categories. The grassland definition in the IPCC includes rangelands and pasture land that is not considered as Cropland, as well as systems with vegetation that fall below the threshold used in the Forest land category (same explanation as for Cropland). This category also includes all grassland from wild lands to recreational areas as well as agricultural and silvo-pastoral systems, subdivided into managed and unmanaged, consistent with national definitions (Petrescu et al., 2021b). For similar reasons to those expressed in the section Cropland above, the current work (Fig. 7) compares modeled CO_2 flux against NGHGI results for total Grassland (GL).

The NGHGIs of countries in the EU27 report emissions from managed pastures and grasslands, although the details of what is included varies between countries (Table 6.22, EU

NIR, 2022). Grasslands can be managed through grazing or by cutting. If a grassland is used for grazing but retains the natural vegetation, it is called a “rangeland”. If the area has been replanted with vegetation specifically for animal forage, it is commonly referred to as “pasture”[7]. Since almost all European grasslands are somehow modified by human activity and to a major extent have been created and maintained by agricultural activities, they can be defined as “semi-natural grasslands”, even if their plant communities are natural (Silva et al., 2008).

The NGHGI reports a slightly positive net flux over 1990-2018. Both ORCHIDEE and EPIC-IIASA show a strong sink in 2021, consistent with previous years, although the value for ORCHIDEE is quite extreme for that year. Explanations for the differences in Fig. 7 remain identical to those given in McGrath et al. (2023), including more favourable growing conditions leading to a stronger sink, differences between Tier 1 and Tier 3 approaches in terms of modelling sinks, and consideration of only drained organic soils.

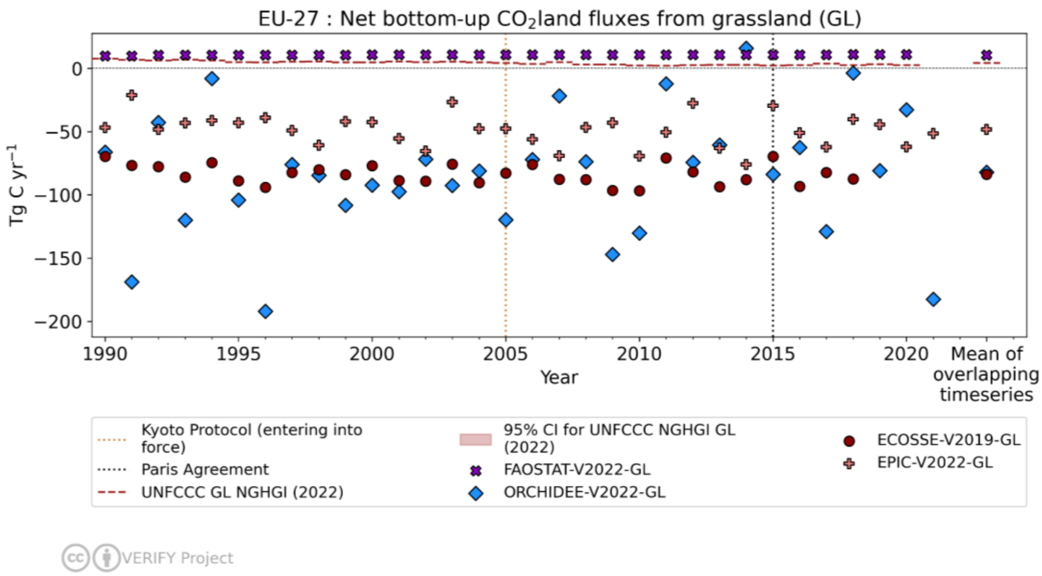

Figure 7: Net CO_2 land flux from total Grassland (GL) estimates for EU27 from updated datasets considered here. The means shown on the right of each plot are for 1990-2018. GL net carbon fluxes are estimated with the ORCHIDEE, EPIC-IIASA, and ECOSSE (not updated and therefore identical to McGrath et al., 2023) models in addition to FAOSTAT. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

The same time series for all individual EU countries are also available from the following link:
https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=GrasslandRemain

Similar features are obtained for individual countries with large year to year variability of the grassland sink simulated by ORCHIDEE and a much stronger sink in 2021 compared to

[7] See, for example, https://www.epa.gov/agriculture/agricultural-pasture-rangeland-and-grazing

2020 for most countries (except for Finland, Spain, Bulgaria, Croatia and Greece), due to climate variability. Further analysis is on-going.

4.4.2 Bottom-up CO_2 estimates from all LULUCF categories

This section analyzes CO_2 emissions and sinks for the LULUCF sector, including NGHGI and a suite of different bottom-up approaches. This comparison is challenging due to differences in terms of activities covered in the different estimates, as well as differences in terminology (see, for example, Petrescu et al., 2020, Fig. 12). In the interest of saving space, the interested reader is referred to Petrescu et al. (2021b) and McGrath et al. (2023) for further discussion. Given all these differences in terms of activities, the comparison in this section should be considered as a rough overview that highlights both important aspects of the C cycle and questions that need to be addressed in the future.

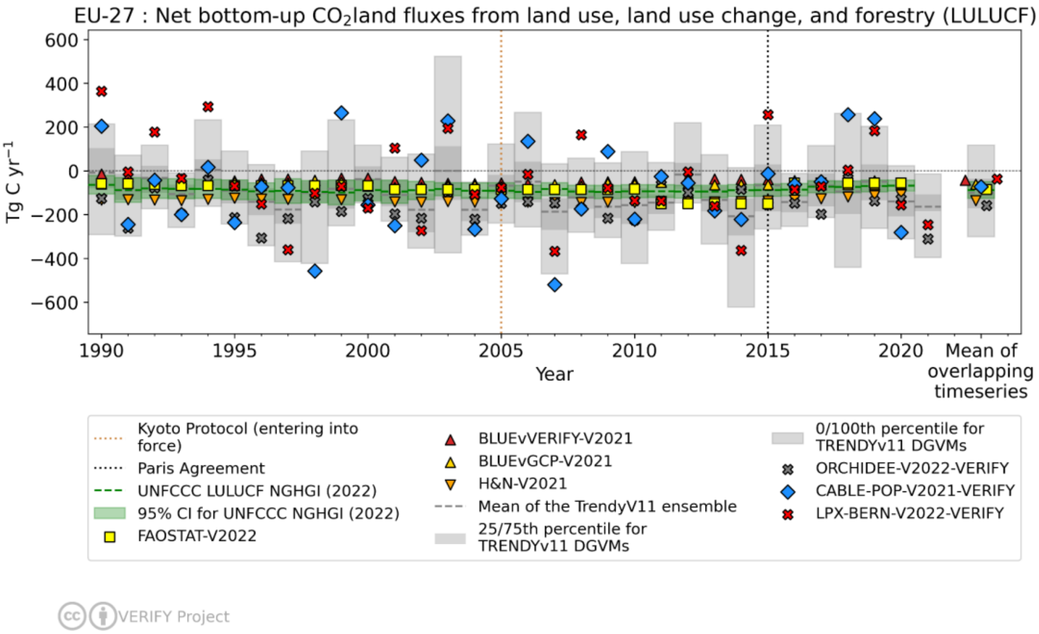

Figure 8: Net CO_2 fluxes from total LULUCF activities in the EU27 from: UNFCCC NGHGI (2022), BLUE (vVERIFY), BLUE (vGCP2021), H&N (GCP2021), DGVMs (TRENDY v11), FAOSTAT (2022), and three DGVMs run with high-spatial-resolution (0.125°) meteorological forcing (models thats are also part of the TRENDY ensemble at 0.5°). The gray bars represent the spread of TRENDY models. The UNFCCC estimate includes all classes (remain and convert), as well as HWP. The relative error of the UNFCCC values represent the UNFCCC NGHGI (2022) Member States reported uncertainty computed with the error propagation method (95 % confidence interval), gap-filled and provided for each year of the timeseries. Biomass burning emissions are included in the C stock estimates. The FAOSTAT estimate includes both Forest land remaining forest land in addition to incorporating afforestation and deforestation as conversion of Forest land to other land types. The means are calculated for the 1990–2019 overlapping period. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

Figure 8 shows CO_2 fluxes from the NGHGI LULUCF sector compared to all other comparable bottom-up (BU) estimates in this work: high-resolution S3 simulations for both ORCHIDEE (v2022), CABLE-POP (V2021), and a new addition, LPX-Bern (V2022); the median of 18 S3 simulations from the TRENDYv11 DGVM ensemble; three bookkeeping models (not updated from McGrath et al., 2023); and FAOSTAT (V2022). As mentioned above, taking the difference of the TRENDY S2 and S3 simulations provides an estimate of the net flux from land use change, but inconsistencies are introduced either way, and therefore further research is needed in order to establish which approach (S3-S2, or simply S3) leads to the most consistent comparison. For the overlapping period 1990-2019, the means of two out of the three bookkeeping models (BLUE vGCP (-61 Tg C yr^{-1}) and BLUE vVERIFY (-43 Tg C yr^{-1}, using the Hilda+ land use forcing)) along with the mean of FAOSTAT (-84 Tg C yr^{-1}) fall within the 95 % confidence interval of the UNFCCC NGHGI estimate of -88 ± 38 Tg C yr^{-1}. Only H&N rests apart with a stronger sink (-142 Tg C yr^{-1}).

Bookkeeping models like BLUE and H&N do not include indirect effects on biomass growth due to factors such as CO_2 fertilization, nitrogen deposition, and climate change, while NGHGIs implicitly include these impacts on managed land through updated statistics. As noted by McGrath et al. (2023), recent work by Grassi et al. (2022b) demonstrates that indirect effects are small in the EU27+UK, which likely applies to the EU27 considered here.

The UNFCCC LULUCF estimates contain CO_2 emissions from all six land use categories and HWP, including remaining categories and conversion to and from a category to another. The DGVMs show high interannual variability, as demonstrated clearly by the high-resolution CABLE-POP simulation in Fig. 8. The mean values for DGVMs across the overlapping period also show a large spread: -158 Tg C yr^{-1}, -72 Tg C yr^{-1}, -37 Tg C yr^{-1}, and -100 [-172, -36] Tg C yr^{-1} for ORCHIDEE, CABLE-POP, LPX-Bern, and TRENDY v11, respectively, compared to the NGHGI mean of -88 ± 38 Tg C yr^{-1}. Note again that ORCHIDEE, CABLE-POP, and LPX-Bern are also part of the TRENDYv11 ensemble, but the simulations included in TRENDY used a coarser meteorological forcing than the one used within the VERIFY project (around 0.125° resolution). The increased IAV from the high-resolution CABLE-POP compared to ORCHIDEE is suspected to have been introduced through the construction of the LULCC dataset as described in Appendix A2 in McGrath et al. (2023).

The year 2021 appears to have been a stronger sink than normal for the models providing data for that year (ORCHIDEE, LPX-Bern, and TRENDY v11).

The differences between bookkeeping models and UNFCCC and FAOSTAT are discussed in detail elsewhere, and focus on the inclusion of unmanaged land in bookkeeping models but not FAOSTAT and UNFCCC methodologies (Petrescu et al., 2020; Grassi et al., 2018a, 2021). Differences between the other models are discussed in McGrath et al. (2023), and relate to inter-annual variability.

The same time series for all individual EU countries are also available from the following link:
https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=LULUCFTrendy

Similar remarks and cautions as discussed above apply to the individual country fluxes. Although on average 2021 is a stronger sink than normal, larger differences between countries occur. These differences are under investigation.

4.4.3 Comparison of atmospheric inversions with NGHGI CO_2 estimates

Figure 9 highlights the range of estimates from global and regional atmospheric inversions (GCP2022, EUROCOM, CSR, LUMIA, and CIF-CHIMERE; see Table 2 and Appendix for more details) against bottom-up total annual EU27 CO_2 land emissions/removals from the UNFCCC NGHGI (2022). In these inversions, all components of the carbon cycle that contribute to the observed atmospheric CO_2 gradients between stations are implicitly included as the inversions incorporate observed atmospheric concentrations of CO_2. This includes processes where carbon is uptaken by vegetation in one area and emitted in a different area, i.e. emissions due to the respiration of laterally transported carbon.

As in McGrath et al. (2023), the removal of emissions and sinks from inversion results due to lateral transport of carbon from crop trade, wood trade, and inland waters is included. Bottom-up methods (including all the NGHGIs for European countries) do not consider emissions and removal of atmospheric CO_2 due to lateral transport of carbon, while observations assimilated into top-down inversions record all CO_2 fluxes without separating their components. We followed Eq. (1) of Deng et al. (2021) without prior masking for managed land. Emissions from lateral transport of carbon (“lateral fluxes”) were prepared generally following the approach described by Ciais et al. (2021), where crop and wood product fluxes are derived from country-level trade statistics compiled by the FAO. Inland water emissions and riverine export of terrestrial carbon use spatially explicit climatological data and a statistical model combined with estimates of gas transfer velocities. A more complete description is given in Appendix. This adjustment has been applied to all top-down fluxes reported here unless indicated otherwise.

As in McGrath et al. (2023), the C fluxes from inland waters (rivers and lakes) is based on maps of sinks/sources of rivers/lakes, wood and crops, accounting for a combined mean of -135 Tg C yr^{-1} (over the 2015-2018 common period of the inversions). For comparing bottom-up methods (including the NGHGI) to TD estimates in the EU27, it is always necessary to remove the traded wood and crop harvest (see Deng et al. (2021) and McGrath et al. (2023) for additional explanations).

Flux estimates from inversion methods for CO_2 land show much more variability than the NGHGI (Fig. 9). The mean of the EUROCOM ensemble of European inversions shows good agreement with UNFCCC NGHGI data, but with a huge spread of annual model results that extends from significant sources into large sinks. This large spread can be linked to uncertainty in atmospheric transport modeling, inversion methods and assumptions, and to limitations of the observation system. Furthermore, the EUROCOM inversions were designed for the European geographical domain (which is larger than the EU27) and are still being developed in particular to better constrain the latitudinal and longitudinal boundary conditions.

The annual mean (overlapping period 2015-2018) of the EUROCOM v2021 inversions (-89 [-170,-21] Tg C yr^{-1}) is the closest inversion estimate to the timeseries mean of the NGHGI estimates (-80 ± 27 Tg C yr^{-1}), where the error bars for the inversion indicate the [0^{th},100^{th}] percentiles due to the small size of the ensembles. The mean of the global GCP2022 inversions (-55 [-173,+44] Tg C yr^{-1}) and the regional inversion LUMIA (-61 [-101,-7] Tg C yr^{-1}) show a lower absolute value, but report larger interannual variability (min/max). The CIF-CIMERE product has a mean of -73 Tg C yr^{-1}, in good agreement with the others, but showing extremely positive fluxes before 2010, which is not seen in other models and is still under investigation. The most recent CSR regional inversion ensemble shows a much stronger sink than the other models, with a value of -197 [-271,-82] Tg C yr^{-1}. Year 2021 is only available for two datasets, GCP2022 and CSR, and displays no deviation from previous years.

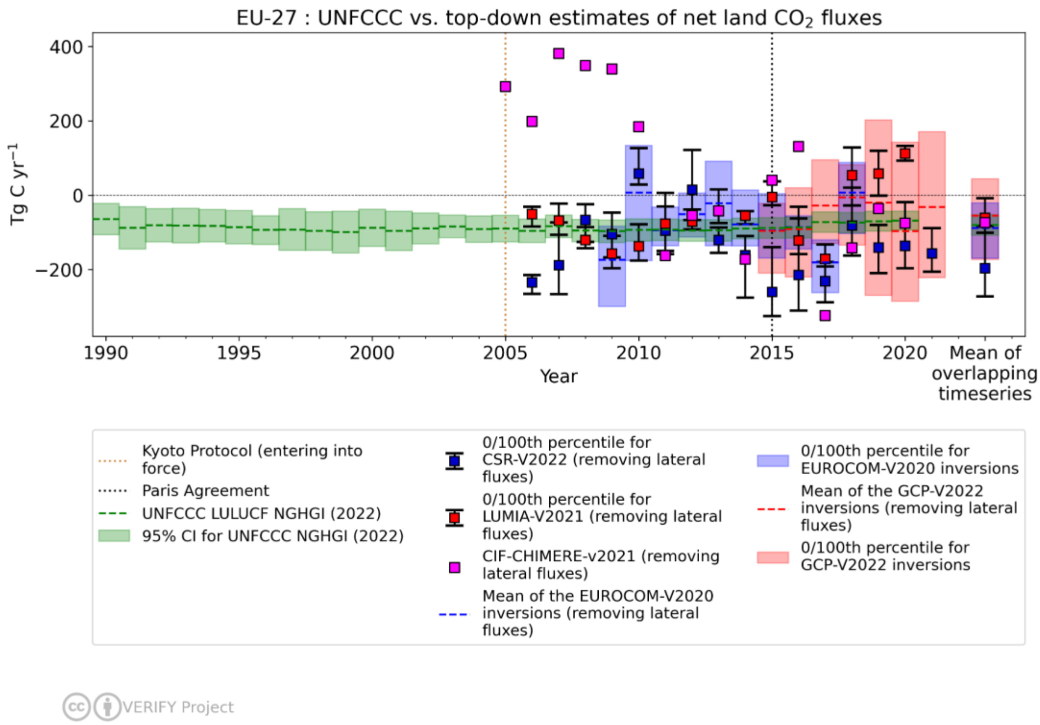

Figure 9: Comparison of inventories and atmospheric inversions for the total EU27 biogenic CO_2 fluxes. Top-down inversion results are: the global GCB2022 ensemble, the regional EUROCOM ensemble, the regional CarboScopeReg model with multiple variants, the regional LUMIA model with multiple variants, and CIF-CHIMERE. The relative error in the UNFCCC values represents the UNFCCC NGHGI (2022) Member states reported uncertainty computed with the error propagation method (95 % confidence interval) gap-filled and provided for every year of the timeseries. The timeseries mean overlapping period is 2015-2018. The colored area represents the min/max of model ensemble estimates. Emissions due to lateral fluxes of carbon through rivers, crop trade, and wood trade are removed from the top-down estimates. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

The same time series for all individual EU countries are also available from the following link:
https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE&selectFCO2land=TopDownAndInventories

The extremely strong sink seen by CSR for the EU27 is not reproduced over all countries: CSR fluxes are higher than the others in Hungary and the Netherlands, for example, while matching well the NGHGI in Germany, Poland, and Belgium. On the other hand, results for Italy, Finland, and Sweden reflect the pattern seen in the EU27. The bias is therefore not systematic but depends strongly on the region. Further investigation on country specific differences are on-going.

Table 3 below highlights the processes included in the CO_2 land models presented in this work, as these processes are seen for the moment as the main cause of discrepancies between estimates shown in all the previous figures.

Table 3: Comparison of the processes included in the inventories, bottom-up models and inversions.

Descri-ption	**NGHGI**	**Global database**	**Process-based models**				**DGVMs**			**Bookkeeping Models**			**Inversions[#]**	
	UNFCCC[a]	FAOSTAT[a]	ECOSSE	EPIC-IIASA	CBM	EFISCEN-SPACE	CABLE-POP	TRENDY v11	ORCHIDEE	BLUE vGCP	BLUE vVERIFY	H&N	Regional inversions (CSR, LUMIA, CIF-CHIMERE, EUROCOM)	Global Inversions (GCP)**
Ecosystem split / LC transitions														
Forest total	E	E	N	N	E	E	E	Acc. table A2 in GCB 2022 (Friedlingstein et al., 2022)	E	E[h]	E[h]	E[h]		Acc. Table A3 in GCB 2022 (Friedlingstein et al 2022)
Split FL-FL / FL-X / X-FL	E	E	N	N	E	E/N/N	E		E	E[h]/E/E	E[h]/E/E	E[h]/E/E		
Cropland total	E	N	E	E	N	N	I		E	E[h]	E[h]	E[h]		
Split CL-CL / CL-X / X-CL	E	N	E	E/N/N	N	N	I		E	N/E/E	N/E/E	N/E/E		
Grassland total	E	N	E	N	N	N	E		E	E	E	E		
Split GL-GL / GL-X / X-GL	E	N	E	N	N	N	E		E	N/E/E	N/E/E	N/E/E		
Peatland accounting	E	E	N	N	N	N	N		N	N	N	N		
"Natural" Processes														
CO_2 fertilization	I	I	N	E	N	N	E	Acc. table A1 in GCB 2022 (Friedlingstein et al., 2022)	E	N[i]	N[i]	N[i]		Acc. Table A3 in GCB 2022 (Friedlingstein et al 2022)
Climate induced	I	I	N	E[f]	I[b]	I[c]	E		E	N[i]	N[i]	N[i]		

impacts														
Natural disturbances (fires, insect, wind)	I	I	N	N	E	N	E		N	N[i]	N[i]	N[i]		
Soil Organic C dynamic	I		E	E	E	E	E		E	N	N	N		
Lateral C transport (river)	N	N	N	N	N	N	N		N	N	N	N		
Direct human-induced processes														
Flux from Harvested Wood Products	E	N	N	N	I	N[d]	E	Acc. table A1 in GCB 2022 (Friedlingstein et al., 2022)	E	E	E	E		Acc. Table A3 in GCB 2022 (Friedlingstein et al 2022)

Not included : **N,** Explicitly modeled : **E,** Implicitly modeled: **I,** Partly modeled : **P**

[a]UNFCCC and FAOSTAT are ensemble of country estimates calculated with specific methodology for each country, following some guidelines

[b]The climate effects can be estimated indirectly by CBM, using external additional input provided by other models

[c]EFISCEN Space: Increment is sensitive to weather, but average weather

[d]EFISCEN has only production in m^3 but doesn't have a direct HWP module

[e]Crop yield and residue harvest from cropland (20 % of residues harvested in case of cereals, no residue harvest for other crops)

[f]EPIC-IIASA partly accounts for soil drought, i.e., plant growth limitation due to a lack of water in the soils. Heat stress and floods are not accounted for, though

[g]In principle, burning of crop residues on cropland can be explicitly simulated by EPIC-IIASA. However, not done for VERIFY as it is not a relevant scenario for the business as usual cropland management in Europe

[h]forest/cropland/grassland exist and have carbon stocks, but have carbon fluxes only through change to management. FL-FL includes all land-use induced effects (harvest slash and product decay, regrowth after agric abandonment and harvesting)

[i]implicit by using observation-based carbon densities that reflect harvest/climate/natural disturbances

[j]peat burning and peat drainage are not bookkeeping model output, but are added from various data sources during post processing

[*]According Table 2 in Monteil et al. (2020) and Table A3 in Friedlingstein et al. (2019)

[#]These categories are inputs to the inversions, not a result; the inversions adjust the total land-atmosphere C flux, regardless of what went into the prior, and the posterior flux cannot really be disaggregated into contributions from separate processes. In a sense, as long as a process is sufficiently significant to influence the CO_2 observations, it will have an impact on the inversion results

According to Table 3, no bottom-up model or dataset used here contains all of the 13 LULUCF categories reported in the NGHGIs. As shown in McGrath et al. (2023), six categories account for almost 90 % of the gross flux: Forest land remaining forest land (56 %), Land converted to cropland (7 %), Land converted to forest land (7 %), Grassland remaining grassland (6 %), Harvested wood products (6 %), and Land converted to settlements (6 %). DGVMs currently include more of these categories than other methods. However, the number of categories included may not be a good proxy for quality of comparison. While an ideal model would include all categories in the NGHGI, it must also represent these categories well. Figures 4-7 suggest that sector-specific models currently show better agreement with the NGHGI than DGVMs, although a more detailed analysis including the entire suite of TRENDY models would be insightful.

4.4.4 Uncertainties in top-down and bottom-up estimates

Uncertainties are essential for complete comparisons between models and approaches. This section summarizes the main sources of uncertainty estimates interwoven throughout the above text. A more full discussion is given in McGrath et al. (2023).

Several sources of uncertainty arise from the synthesis of bottom-up (BU) inventories and models of carbon fluxes, which can be summarized as: (a) differences due to input data and structural/parametric uncertainty of models (Houghton et al., 2012) and (b) differences in definitions (Pongratz et al., 2014; Grassi et al., 2018b, 2021; Petrescu et al., 2020, 2021b). Posterior uncertainties in top-down (TD) estimates mostly come from: 1) errors in the modeled atmospheric transport; 2) aggregation errors, i.e., errors arising from the way the flux variables are discretized in space and time and error correlations in time; 3) errors in the background mole fractions; and 4) incomplete information from the observations and hence the dependence on the prior fluxes.

Figure 10 summarizes the quantifiable uncertainties in this work. With the exception of the NGHGI, all the other uncertainties are calculated from ensembles of simulations using either: 1) multiple models of the same general type, either using model-specific inputs or attempting to harmonize inputs as much as possible (e.g., TRENDY), or 2) multiple simulations with the same model, varying input parameters and/or forcing data (e.g., CarboScopeRegional, LUMIA). As a complete characterization of model uncertainty involves exploring the full parameter, input data, and model structure space, none of the uncertainties reported here can be considered “complete”, but they represent best estimates given realistic constraints of resources and knowledge. The uncertainties represent the mean of overlapping period (2015-2018). The largest spread comes from the bottom-up DGVMs (TRENDY v11), the 25-75th percentile of which covers 420 Tg C yr^{-1}. Regional and global inversions have a 0--100th percentile spread around 200 Tg C yr^{-1}, while the 95% confidence interval of the NGHGI is the smallest at 56 Tg C yr^{-1}.

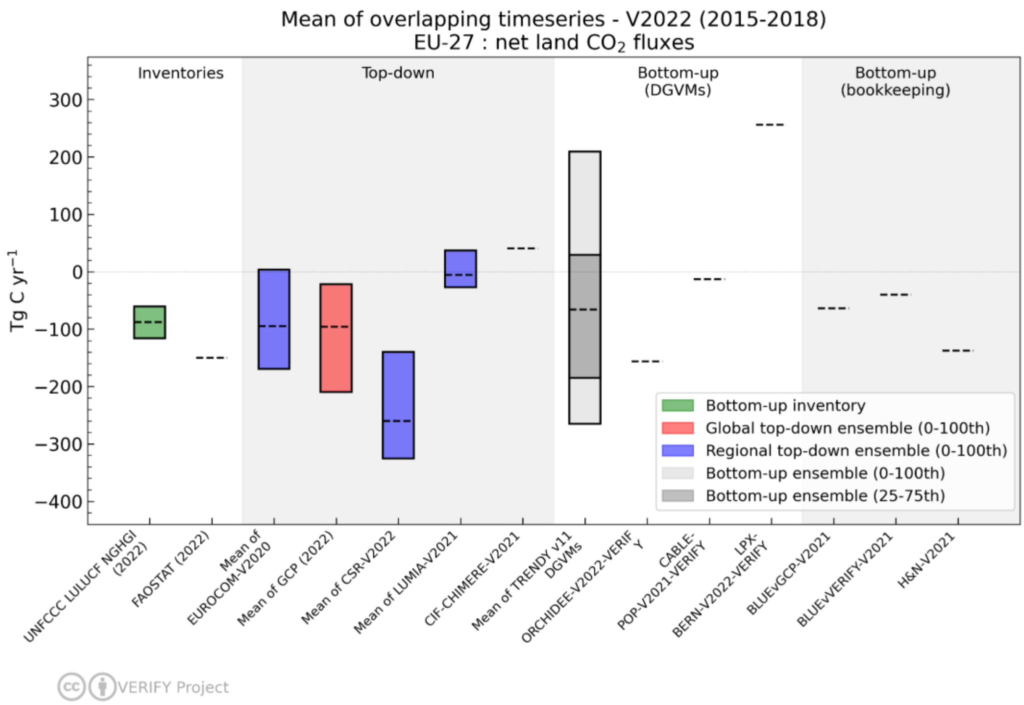

Figure 10: Mean annual values of overlapping time period (2015-2018) (Fig. 8 and 9, Sect. 3.3.4 and 3.3.5). The colored boxes depict the values for ensembles of multiple models, with the top and bottom of the boxes corresponding to minimum and maximum mean values of the overlapping period. For non-ensemble models (e.g., CIF-CHIMERE, FAOSTAT) the mean of the overlapping period is given by black dashed lines. The NGHGI UNFCCC uncertainty is calculated for submission year 2021 as the relative error of the NGHGI value, computed with the 95 % confidence interval method gap-filled and provided for every year of the timeseries. Inversions have been corrected for emissions of CO_2 from lateral transport of carbon using identical datasets. The fluxes follow the atmospheric convention, where negative values represent a sink while positive values represent a source.

The same time series for all individual EU countries are also available from the following link:
https://webportals.ipsl.fr/VERIFY/FactSheets/display.php?regions=AUT,BEL,BGR,CYP,CZE,DEU,DNK,ESP,EST,FIN,FRA,GBR,GRC,HRV,HUN,IRL,ITA,LTU,LUX,LVA,MLT,NLD,POL,PRT,ROU,SVK,SVN,SWE,E27&selectFCO2land=MeanPlot
Although similar features occur with the largest spread obtained from the DGVMs, country specific differences occur and these are under investigation.

5 Conclusion

This work represents an update of the McGrath et al. (2023) European CO_2 synthesis paper presenting and investigating differences between the UNFCCC NGHGI, BU data-based inventories, both coarse and high-resolution process-based BU models, and TD approaches represented by both global and regional inversions. Datasets used in the previous work have been updated by extending the temporal coverage and updating the models and data behind the calculations. In addition, several new models to expand the number of independent approaches compared have been added. The scope of the analysis has been narrowed to the European Union no longer including the United Kingdom, but providing some additional observations on individual countries. When possible, the behavior of the fluxes in the year 2021 has been highlighted.

CO_2 fossil emissions dominate the anthropogenic CO_2 flux in the EU27, regardless of the approach employed and irrespective of uncertainties. Fossil CO_2 emissions are more straightforward to estimate than ecosystem fluxes due to combustion being easier to model and parameterize at large scales, assuming accurate fossil data is available. A suite of eight BU methods for fossil CO_2 emissions are within the uncertainty of the NGHGI when methods are harmonized to include similar categories. The remaining differences can often be attributed to definitions, assumptions about activity data or emission factors, and the allocation of fuel types to different sectors (see Sect. 4.3). Multiple results from one TD model, a regional European inversion system (CIF-CHIMERE) using different proxy sources, show broad agreement with the BU estimates. However, this initial TD inversion is not yet capable of distinguishing the minor differences between the various BU estimates and does not yet quantify uncertainties. A substantial decrease in the level of uncertainty of the inverse modeling system is expected in the near-term with the large-scale deployment of observation networks dedicated to detecting fossil fuel emissions (e.g., with launch of the CO_2M[8] satellite mission in 2025).

The CO_2 land fluxes belong to the LULUCF sector, which is one of the most uncertain sectors in UNFCCC reporting. The IPCC guidelines prescribe methodologies that are used to estimate the CO_2 fluxes in the NGHGI, but grant countries significant freedom to adopt methods appropriate to their national circumstances. When analyzing the different estimates from multiple BU sources (inventories and models) similar sources of uncertainties are observed such as: (a) differences due to input data and structural/parametric uncertainty of models (Houghton et al., 2012; Pongratz et al., 2021) and (b) differences in definitions (Pongratz et al., 2014; Grassi et al., 2018b; Petrescu et al., 2020, 2021b; Grassi et al., 2021). Reducing uncertainties in LULUCF estimates is needed given the increasing importance of the sector to EU climate policy over the next decades. In contrast to the previous 2020 climate and energy package, the LULUCF sector will now formally contribute to the binding emission reduction targets of the Unions 2030 climate and energy framework (EU, 2018a; 2018b). Furthermore, the European Climate Law explicitly states that LULUCF, together with all sectors of the economy, should contribute to achieving Climate neutrality within the Union by 2050 (EU, 2021b).

The LULUCF sector in NGHGIs is composed of six land use categories. Of these, Forest land provides the most important contribution to the net CO_2 land flux in the EU27, followed by Cropland and Grassland. HWP and "Land converted to settlements" also have non-negligible contributions, and changes in HWP strongly influence variations in decennial mean net LULUCF fluxes for the region. Of these, all except "Land converted to settlements" are represented in general ecosystem models, while Forestland, Cropland, and Grassland are simulated by sector-specific process-based and data-driven models. Top-down inversions are capable of simulating net CO_2 fluxes to the atmosphere, but cannot yet attribute them between different categories.

[8] CO_2M: Copernicus Anthropogenic Carbon Dioxide Monitoring, https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf

Differences in the detailed sector-specific and inversion model results (Fig. 4-9) often come from choices in the simulation setup and the type of model used: bookkeeping models, process-based DGVMs, inventory-based statistical methods, or atmospheric inversions. Results also differ based on whether fluxes are attributed to LULUCF emissions due to the cause or location of occurrence. For example, indirect fluxes on managed land are included in NGHGI and FAOSTAT, while additional sink capacity (e.g., Petrescu et al., 2021b, McGrath et al., 2023) is included in estimates from process-based models (e.g., ORCHIDEE or TRENDY DGVMs). The use of gross land use changes fluxes (e.g., in the NGHGI, bookkeeping models, and CABLE-POP) as opposed to net fluxes also likely plays an important role.

Observation-based BU estimates of LULUCF provide large year-to-year flux variability (Fig. 4-7, in particular for DGVMs like ORCHIDEE, CABLE-POP and the TRENDY ensemble), contrary to the NGHGI, primarily due to the effect of varying meteorology. In particular, the duration and intensity of the summer growing season can vary significantly between years (e.g., Bastos et al., 2020a; Thompson et al., 2020). In the framework of periodic NGHGI assessments, the choice of a reference period (such as 2015-2019, as used here) or the use of a moving window to calculate the means may be critical to smooth out high inter-annual variability and facilitate comparisons. One can also imagine incorporating IAV into the NGHGIs through the use of annual anomalies of emission factors calculated from Tier 3 observation-based approaches (either BU or TD). TD estimates also show very large inter-annual variability (Fig. 9). Uncertainties in the inversion results are primarily due to uncertainties in atmospheric transport modeling, boundary conditions, technical simplifications and uncertainty inherent to the limitation of the observation network. Currently, regional inversions (LUMIA, CSR and EUROCOM) are still under development and face different challenges from the coarser resolution global systems used here to represent regional results (GCP). Based on this work, it is difficult to claim that one or the other provides a more accurate result for the net CO_2 land fluxes across the EU27.

As seen in figures throughout this work, reducing uncertainties of both individual models and classes of models remains a priority. Some categories (Forestland, Cropland) produce results for multiple category-specific models closely tracking the NGHGI. This likely reflects the use of data-driven models and the relatively high quality of data that is available due to the economic importance of these categories. On the other hand, generalized ecosystem models (the DGVMs, like ORCHIDEE and LPX-Bern) may create mean estimates which fall within uncertainties, but fall outside of NGHGI uncertainties for any given year due to the sensitivity of processes in these models to rapidly changing meteorology and the necessity for these models to operate globally, including in data-poor regions for which parameterization may be impossible. A more detailed analysis of LULUCF fluxes at the regional/country level is foreseen as part of projects linked to CoCO2 and VERIFY including the RECCAP2 initiative (RECCAP2, 2022) and current and future Horizon Europe funded projects (e.g., CoCO2, EYE-CLIMA, AVENGERS, PARIS) which will highlight examples of good practice in LULUCF flux monitoring amongst European countries. Sect. 3.3.6 presents a summary of uncertainties to provide insight into ground observation systems assimilated by inversions. This lays the basis of future improvements for establishing best practices on how to configure atmospheric inversions and systematically quantify uncertainties.

The next steps needed to improve and facilitate the reconciliation between BU and TD estimates are the same as those discussed in McGrath et al. (2023): 1) BU process-based models incorporating unified protocols and guidelines for uniform definitions should be able to disaggregate their estimates to facilitate comparison to NGHGI and 2006 IPCC practices (e.g., managed vs. unmanaged land, 20-year legacy for classes remaining in the same class, distinction of fluxes arising solely from land use change, Grassi et al. (2022a)); 2) for sector-specific models, in particular for cropland and grassland, improving treatment of the contribution of soil organic carbon dynamics to the budget; 3) for TD estimates, using the recently developed Community Inversion Framework (Berchet et al., 2021) to better assess the different sources of uncertainties from the inversion set-ups (model transport, prior fluxes, observation networks), 4) standardize methods to compare datasets with and without interannual variability, and 5) develop a clear way to report key system boundary, data, or definitional issues, as it often necessary to have deep understanding of each estimate to know how to do a like-for-like comparison.

Similar to McGrath et al. (2023), this updated study concludes that a complete, ready-for-purpose monitoring system providing annual carbon fluxes across Europe is still under development, but data sources are beginning to show improved agreement compared to previous estimates. Therefore significant effort must still be undertaken to reduce the uncertainty across all potential methods (i.e., structural uncertainty in the models as well as the input data supplied to the models or inventory approaches) used in such a system (e.g. Maenhout et al., 2020).

Achieving the well-below 2ºC temperature goal of the Paris Agreement requires, among other things, low-carbon energy technologies, forest-based mitigation approaches, and engineered carbon dioxide removal (Grassi et al., 2018a; Nabuurs et al. 2017). Currently, the EU27 reports a sink for LULUCF and forest management will continue to be the main driver affecting the productivity of European forests for the next decades (Koehl et al., 2010), shown as well by the domination of Forestland CO_2 fluxes to the LULUCF sector in the NGHGI for the bloc. Forest management changes forest composition and structure, which affects the exchange of energy with the atmosphere (Naudts et al., 2016), and therefore the potential of mitigating climate change (Luyssaert et al., 2018; Grassi et al., 2019). Meteorological extremes can also affect the efficiency of the sink (Thompson et al., 2020). The EU forest sink is projected to decrease in the near future (Vizzarri et al., 2021). Consequently, for the EU to meet its ambitious climate targets, it is necessary to maintain and even strengthen the LULUCF sink (EU, 2020). Understanding the evolution of the CO_2 land fluxes is critical to enable the EU27 to meet its ambitious climate goals.

6 Appendices

6.1 Terminology

Table 6.1.1: A short list of terminology and acronyms used in this work. Note that nuances may be lost due to space limitations, and therefore these definitions should be considered as a guide.

Terminology/Acronym	Brief description
Top-down (TD)	A model which solves for fluxes by optimizing a prior guess based on observed atmospheric concentrations. Also called an "atmospheric inversion".
Bottom-up (BU)	A model which estimates fluxes by through physical processes and/or data without explicit consideration of atmospheric gas concentrations. Often subdivided into "data-driven" and "process-based", and include "inventories".
GHG	Greenhouse gases (generally CO_2 in this work)
LULUCF	Land use, land use change, and forestry
NGHGI	National greenhouse gas inventory
DGVM	Dynamical global vegetation model, a form of bottom-up model.
Annex I Parties	A designation of countries under the UNFCCC. Includes most industrialized countries and economies in transition as determined in 1992. Required to submit more regular and complete inventories to the UNFCCC.
UNFCCC	United Nations Framework Convention on Climate Change
GCB	Global Carbon Budget
VERIFY	A project funded by the European Commission to build a pre-operational greenhouse gas monitoring system (see Appendix A)
FL-FL	Forest land which remains forest land from year to year
CL-CL	Cropland which remains cropland from year to year
GL-GL	Grassland which remains grassland from year to year

HWP	Harvested wood products. Carbon in timber removed from forest land is counted here and allowed to slowly decompose (i.e., release CO_2 to the atmosphere).

6.2 Fossil CO_2 emissions

6.2.1 Bottom-up emission estimates

For further details of all datasets, see Andrew (2020).

UNFCCC NGHGI (2023)

Annex I NGHGIs should follow principles of transparency, accuracy, consistency, completeness and comparability (TACCC) under the guidance of the UNFCCC (UNFCCC, 2014) and as mentioned above, shall be completed following the 2006 IPCC guidelines (IPCC, 2006). In addition, the IPCC 2019 Refinement (IPCC, 2019), which may be used to complement the 2006 IPCC guidelines, has updated sectors with additional emission sources and provides guidance on the use of atmospheric data for independent verification of GHG inventories.

Both approaches (BU and TD) provide useful insights on emissions from two different points of view. First, as outlined in Volume 1, Chapter 6 of the 2019 IPCC Refinement (IPCC, 2019), TD approaches act as an additional quality check for BU and NGHGI approaches, and facilitate a deeper understanding of the processes driving changes in different elements of GHG budgets. Second, while independent BU methods do not follow prescribed standards like the IPCC Guidelines, they do provide complementary information based on alternative input data at varying temporal, spatial, and sectoral resolution. This complementary information helps build trust in country GHG estimates, which form the basis of national climate mitigation policies. Additionally, BU estimates are needed as input for TD estimates. As there is no formal guideline to estimate uncertainties in TD or BU approaches, uncertainties are usually assessed from the spread of different estimates within the same approach, though some groups or institutions report uncertainties for their individual estimates using a variety of methods, for instance, by performing Monte Carlo sensitivity simulation by varying input data parameters. However, this can be logistically and computationally difficult when dealing with complex process-based models.

Despite the important insights gained from complementary BU and TD emission estimates, it should be noted that comparisons with the NGHGI are not always straightforward. BU estimates often share common methodology and input data, and through harmonization, structural differences between BU estimates and NGHGIs can be interpreted. However, the use of common input data restricts the independence between the datasets and, from a verification perspective, may limit the conclusions drawn from the comparisons. On the other hand, TD estimates are constrained by independent atmospheric observations and can serve as an additional, nearly independent quality check for NGHGIs. Nonetheless, structural differences between NGHGIs (what sources and sinks are included, and where and when emissions/removals occur) and the actual fluxes of GHGs to the atmosphere must be taken into account during comparison of estimates. While NGHGIs go through a central QA/QC review process, the UNFCCC reporting requirements do not mandate large-scale observation-derived verification. Nevertheless, the individual countries may use atmospheric data and inverse modeling within their data quality control, quality assurance and verification processes, with expanded and updated guidance provided in chapter 6 of the 2019 Refinement of IPCC 2006 Guidelines (IPCC, 2019). So far, only a few countries (e.g. Switzerland, UK, New Zealand and Australia) have used atmospheric observations to constrain national emissions and documented these verification activities in their national inventory reports (Bergamaschi et al., 2018), and none do so for CO_2.

Under the UNFCCC convention and its Kyoto Protocol, national greenhouse gas (GHG) inventories are the most important source of information to track progress and assess climate protection measures by countries. In order to build mutual trust in the reliability of GHG emission information provided, national GHG inventories are subject to standardized reporting requirements, which have been continuously developed by the Conference of the Parties (COP)[2]. The calculation methods for the estimation of greenhouse gasses in the respective sectors is determined by the methods provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These Guidelines provide detailed methodological descriptions to estimate emissions and removals, as well as recommendations to collect the activity data needed.

As a general overall requirement, the UNFCCC reporting guidelines stipulate that reporting under the Convention and the Kyoto Protocol must follow the five key principles of transparency, accuracy, completeness, consistency and comparability (TACCC). The three main GHGs are reported in timeseries from 1990 up to two years before the due date of the reporting (i.e., t-2). The reporting is strictly source category based and is done under the Common Reporting Format tables (CRF), downloadable from the UNFCCC official submission portal: https://unfccc.int/ghg-inventories-annex-i-parties/2021.

The UNFCCC NGHGI CO_2 emissions/removals include estimates from five key sectors for the EU27: 1 Energy, 2 Industrial processes and product use (IPPU), 3 Agriculture, 4 LULUCF and 5 Waste. The tier method a country applies depends on the national circumstances and the individual conditions of the land, which explains the variability of uncertainties among the sector itself as well as among EU countries. This annual published dataset includes all CO_2 emissions sources for those countries, and for most countries for the period 1990 to t-2. Some eastern European countries' submissions began in the 1980s.

NGHGI uncertainties

Uncertainties for the NGHGI estimates have not been updated for V2022, and thus the details are identical to those provided in the Appendix of McGrath et al. (2023). In summary, the presented uncertainties in the reported emissions of the individual countries and the EU27 bloc were calculated by using the methods and data used to compile the official GHG emission uncertainties that are reported by the EU under the UNFCCC (EU NIR, 2022). This requires accounting for incompleteness in uncertainties reported by countries for various sectors and gap-filling at the individual GHG level, using assumptions of correlation depending on if default or country-specific emission factors are used.

EDGAR

The first edition of the Emissions Database for Global Atmospheric Research was published in 1995. The dataset now includes almost all sources of fossil CO_2 emissions, is updated annually, and reports data for 1970 to year t-1. Estimates for v7.0 are provided by sector. Emissions are estimated fully based on statistical data from 1970 till 2019 (https://edgar.jrc.ec.europa.eu/dataset_ghg70).

Uncertainties: EDGAR uses emission factors (EFs) and activity data (AD) to estimate emissions. Both EFs and AD are uncertain to some degree, and when combined, their uncertainties need to be combined too. To estimate EDGAR's uncertainties (stemming from lack of knowledge of the true value of the EF and AD), the methodology devised by IPCC (2006, Chapter 3) is adopted, that is the overall uncertainty is the square root of the sum of squares of the uncertainty of the EF and AD (uncertainty of the product of two variables). A log-normal probability distribution function is assumed in order to avoid negative values, and uncertainties are reported as the 95 % confidence interval according to IPCC (2006, chapter 3, equation 3.7). For emission uncertainty in the range 50 % to 230 % a correction factor is adopted as suggested by Frey et al. (2003) and IPCC (2006, chapter 3, equation 3.4). Uncertainties are published in Solazzo et al. (2021).

BP

BP releases its Statistical Review of World Energy annually in June, the first report being published in 1952. Primarily an energy dataset, BP also includes estimates of fossil-fuel CO_2 emissions derived from its energy data (BP 2011, 2017). The emissions estimates are totals for each country starting in 1965 to year t-1.

CDIAC

The original Carbon Dioxide Information Analysis Center included a fossil CO_2 emissions dataset that was long known as CDIAC. This dataset is now produced at Appalachian State University, and has been renamed CDIAC-FF (CDIAC, 2022). It includes emissions from fossil fuels and cement production from 1751 to year t-3. Fossil-fuel emissions are derived from UN energy statistics, and cement emissions from USGS production data.

EIA

The US Energy Information Administration publishes international energy statistics and from these derives estimates of energy combustion CO_2 emissions. Data are currently available for the period 1980-2021.

IEA

The International Energy Agency publishes international energy statistics and from these derives estimates of energy combustion CO_2 emissions including from the use of coal in the iron and steel industry. Emissions estimates start in 1960 for OECD members and 1971 for non-members, and run through t-1 for OECD members' totals, and year t-2 for members' details and non-members. Estimates are available by sector for a fee.

GCP

The Global Carbon Project includes estimates of fossil CO_2 emissions in its annual Global Carbon Budget publication. These include emissions from fossil fuels and cement production for the period 1750 to year t-1.

CEDS

The Community Emissions Data System has included estimates of fossil CO_2 emissions since 2018, with an irregular update cycle (CEDS, 2022). Energy data are directly from IEA, but emissions are scaled to higher-priority sources, including national inventories. Almost all emissions sources are included and estimates are published for the period 1750 to year t-1. Estimates are provided by sector.

PRIMAP

The PRIMAP-hist dataset (v2.4.2) combines several published datasets to create a comprehensive set of greenhouse gas emission pathways for every country and Kyoto gas, covering the years 1850 to 2018, and all UNFCCC (United Nations Framework Convention on Climate Change) member states as well as most non-UNFCCC territories. The data resolves the main IPCC (Intergovernmental Panel on Climate Change) 2006 categories. For CO_2, CH_4, and N_2O subsector data for Energy, Industrial Processes and Product Use (IPPU), and Agriculture is available. Due to data availability and methodological issues, version 2.2 of the PRIMAP-hist dataset does not include emissions from Land Use, Land-Use Change, and Forestry (LULUCF).

6.2.2 Top-down CO_2 emission estimates

CIF-CHIMERE - fossil CO_2 emission inversion

CIF-CHIMERE is used for both CO_2 land and CO_2 fossil emission estimates, and this section only describes the CO_2 fossil estimates. The product is explained in more detail by Fortems-Cheiney and Broquet (2022).

We have developed an atmospheric inversion configuration quantifying monthly to annual budgets of the national emissions of fossil CO_2 in Europe based on the assimilation of the long-term series of i) NO_2 satellite spaceborne observations from OMI-QA4ECV (Boersma et al., 2017), ii) NO_2 satellite observations from TROPOMI (Eskes et al., 2021) and iii) CO satellite observations from MOPITT (Deeter et al., 2019); the Community Inversion Framework (CIF); the CHIMERE regional chemistry transport model (CTM); corrections to the TNO-GHGco-v3 inventory of NOx or CO anthropogenic emissions at 0.5° horizontal resolution; and the conversion of NOx or CO anthropogenic emission estimates into CO_2 fossil emission estimates. Results from previous atmospheric inversions of the European fossil CO_2 emissions indicated that there were much larger uncertainties associated with the assimilation of CO data than with that of NO_2 data for such a purpose (Konovalov et al, 2016, Konovalov and Llova, 2019). This explains why in a previous synthesis (McGrath et al., 2023) the CIF-CHIMERE inversions for CO_2 fossil emission estimates were restricted to the assimilation of satellite NO_2

observations. However, the conclusions from Konovalov et al. (2016) and Konovalov and Llova (2018) corresponded to the usage of CO observation from IASI thermal-infrared (TIR) measurements. Here, the inversions use CO near-infrared (NIR) and TIR based observations from MOPITT, which have, in principle, a better sensitivity to CO in the lower troposphere than when using TIR only (Deeter et al., 2013). In particular, they use the MOPITT specific "surface" product rather than total column products. Particular attention is paid in the analysis assessing the consistency between the fossil CO_2 emissions estimates from our processing chain with the fossil CO_2 emission budgets provided by the TNO-GHGco-v3 inventory based on the emissions reported by countries to UNFCCC, which are assumed to be accurate in Europe. The algorithm first optimizes NOx or CO emissions and then assumes a fixed ratio of NOx or CO to fossil CO_2 emissions. However, long-term plans include the simultaneous inversion of all three gases (CO_2, NO_2, and CO).

The analysis is conducted over the period 2005 to 2021 for the NOx-OMI inversions, from 2011 to 2021 for the CO-MOPITT inversions and from 2019 to 2021 for the NOx-TROPOMI inversions. CHIMERE is run over a 0.5°×0.5° regular grid and 17 vertical layers, from the surface to 200hPa, with 8 layers within the first two kilometers. The domain includes 101 (longitude) x 85 (latitude) grid-cells (15.25°W-35.75°E; 31.75°N-74.25°N) and covers Europe. CHIMERE is driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological forecast (Owens and Hewson, 2018). The chemical scheme used in CHIMERE is MELCHIOR-2, with more than 100 reactions (Lattuati, 1997; CHIMERE 2017), including 24 for inorganic chemistry. Initial and boundary conditions for several key gaseous species responsible for the oxidation capacity of the lower atmosphere, including CO, are specified using monthly climatological data from LMDz-INCA global model. Considering the short NO_2 lifetime, we do not consider its import from outside the domain: its boundary conditions are set to zero. Nevertheless, we take into account peroxyacetyl nitrate (PAN) and the associated NOx reservoir for the large-scale transport of NOx.

As expected by the increase in posterior NOx anthropogenic emissions compared to the prior TNO-GHGco-v3 inventory, the national and annual CO_2fossil budgets derived from the NOx inversions are larger than that of this inventory. On the contrary, the inverted CO_2fossil emissions derived from the CO inversions are smaller than those from the TNO-GHGco-v3 inventory. However, these differences are relatively small at national and monthly scales, the emissions derived from the inversions being quite consistent with the TNO-GHGco-v3 inventory. This consistency is explained by the fact that the inversion of the NOx and CO anthropogenic emissions stays relatively close to their prior estimate given by the TNO-GHGco-v3 inventory. This is partly due to a good level of consistency between the inventory and the satellite data. However, the currently large uncertainty in both the observations and in the atmospheric transport modelling also plays a role.

The opposite signs of the corrections applied to the inventory by the NOx and CO inversions raise concerns and questions some of the assumptions underlying our two-step approach for the estimate of CO_2fossil emissions. These points demonstrate the need for a better understanding of the uncertainties, and in particular the potential sources of biases in the two inversion processes before attempting to synthesize the CO and NO_2-based estimates of the CO_2fossil emissions using more advanced approaches.

Uncertainty: There is no uncertainty estimate currently available for this product.

6.3 Land CO_2 emissions/removals

6.3.1 Bottom-up CO_2 estimates

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National inventory agencies update methods and data regularly. As the European Union consists of 27 Member States, each with their own systems, listing differences since the work of McGrath et al. (2023) is not practical. Instead, the interested reader is referred to McGrath et al. (2023) for a basic description, and the National Inventory Report of the European Union for more complete details (EU NIR, 2022).

Uncertainty: Methodology for the NGHGI UNFCCC submissions are based on Chapter 3 of 2006 IPCC Guidelines for National Greenhouse Gas Inventories and is the same as described in Section 9.2.

ORCHIDEE

Updates are due to updated forcing data. Methods are the same as in McGrath et al. (2023).

CABLE-POP

Results from CABLE-POP are identical to those in McGrath et al. (2023).

CO_2 Emissions from inland waters

This dataset is included with the “Emissions from lateral transport of carbon (crops, wood, and inland waters)” dataset below..

CBM

Results from CBM are identical to those in McGrath et al. (2023).

EFISCEN-Space

Results from EFISCEN-Space are identical to those in McGrath et al. (2023).

EPIC-IIASA

Updates are due to updated forcing data. Methods are the same as in McGrath et al. (2023).

ECOSSE (grasslands)

Results from ECOSSE are identical to those in McGrath et al. (2023).

Bookkeeping models

We make use of data from two bookkeeping models: BLUE (Hansis et al., 2015) and H&N (Houghton & Nassikas, 2017). Results from both models are identical to those found in McGrath et al. (2023).

FAOSTAT

FAOSTAT: Statistics Division of the Food and Agricultural Organization of the United Nations provides updates for the LULUCF CO_2 emissions for the period 1990-2020, available at: https://www.fao.org/faostat/en/#data/GT and its sub-domains.

Methods are the same as in McGrath et al. (2023).

TRENDY DGVMs

The TRENDY dataset was updated to V11, which includes an additional year of forcing and extra models.

Emissions from lateral transport of carbon (crops, wood, and inland waters)

Updates are due to updated forcing data. Methods are the same as in McGrath et al. (2023).

6.3.2 Top-down CO_2 emissions estimates

For the regional inversions, atmospheric observations of CO_2 were taken from multiple sources. For CarboScopeRegional, atmospheric observations were taken from the ICOS 2021.1 ATC (ICOS RI, 2021) and the GlobalViewPlus 6.1 product (Schuldt et al., 2021a). For the CIF-CHIMERE inversions, atmospheric observations of CO_2 for the period 2005-2020 were taken from the ICOS 2021.1 ATC (ICOS RI, 2021) and SNO_SIFA L2 (SNO-IFA, 2023) releases, along with data distributed through the GlobalViewPlus 6.1 product (Schuldt et al., 2021a). For LUMIA inversions, atmospheric observations of CO_2 for the period 2006-2018 were taken from the dataset prepared for the 2018 drought task force initiative (Thompson et al., 2020). For the more recent years, data were used from the ICOS 2021.1 ATC release (ICOS RI, 2021), along with data distributed through the GlobalViewPlus 7.0 product (Schuldt et al., 2021b), and, for four sites, data distributed through the World Data Center for Greenhouse Gases.

CarboScope-Regional

Updates are due to updated forcing data. Methods are the same as in McGrath et al. (2023).

LUMIA

Results from LUMIA are identical to those in McGrath et al. (2023).

CIF-CHIMERE - land CO_2

Results from CIF-CHIMERE are identical to those in McGrath et al. (2023) for the biogenic fluxes (fossil emissions are detailed above).

GCP 2022

The GCP ensemble has been updated to the version including year 2021 (Friedlingstein et al., 2022).

EUROCOM

Results from EUROCOM are identical to those in McGrath et al. (2023).

6.4 Input data

CRUERA

Updated to include the year 2021. Methods are the same as in McGrath et al. (2023).

HILDA+

Results from HILDA+ are identical to those in McGrath et al. (2023).

NITROGEN DEPOSITION

Forcing for nitrogen deposition are identical to those in McGrath et al. (2023).

COASTAL OCEAN FLUXES

Forcing for coastal ocean fluxes are identical to those in McGrath et al. (2023).

7 References

Andrew, R. M.: A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, Earth Syst. Sci. Data, 12, 1437–1465, https://doi.org/10.5194/essd-12-1437-2020, 2020.

Arneth, A., Sitch, S., Pongratz, J., Stocker, B. D., Ciais, P., Poulter, B., Bayer, A. D., Bondeau, A., Calle, L., Chini, L. P., Gasser, T., Fader, M., Friedlingstein, P., Kato, E., Li, W., Lindeskog, M., Nabel, J. E. M. S., Pugh, T. A. M., Robertson, E., Viovy, N., Yue, C., and Zaehle, S.: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. Nature Geosci, 10, 79–84, https://doi.org/10.1038/ngeo2882, 2017.

Balkovič, J., Madaras, M., Skalský, R., Folberth, C., Smatanová, M., Schmid, E., van der Velde, M., Kraxner, F., Obersteiner, M.: Verifiable soil organic carbon modeling to facilitate regional reporting of cropland carbon change: A test case in the Czech Republic, J. Environ. Manage., 274, 111206, https://doi.org/10.1016/j.jenvman.2020.111206, 2020.

Balkovič, J., Skalský, R., Folberth, C., Khabarov, N., Schmid, E., Madaras, M., Obersteiner, M., van der Velde, M.: Impacts and Uncertainties of +2°C of Climate Change and Soil Degradation on European Crop Calorie Supply, Earths Future, 6, 373–395, https://doi.org/10.1002/2017EF000629, 2018.

Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B., Xiong, W.: Pan-European crop modeling with EPIC: Implementation, up-scaling and regional crop yield validation, Agric. Syst., 120, 61–75, https://doi.org/10.1016/j.agsy.2013.05.008, 2013.

Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J. P., Weber, U., Reichstein, M., Fu, Z., Anthoni, P., Arneth, A., Haverd, V., Jain, A. K., Joetzjer, E., Knauer, J., Lienert, S., Loughran, T., McGuire, P. C., Tian, H., Viovy, N., and Zaehle, S.: Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity, Science Advances, 6, eaba2724, DOI: 10.1126/sciadv.aba27, 2020a.

Bastos, A., O'Sullivan, M., Ciais, P., Makowski, D., Sitch, S., Friedlingstein, P., Chevallier, F., Rödenbeck, C., Pongratz, J., Luijkx, I. T., Patra, P. K., Peylin, P., Canadell, J. G., Lauerwald, R., Li, W., Smith, N. E., Peters, W., Goll, D. S., Jain, A. K., Kato, E., Lienert, S., Lombardozzi, D. L., Haverd, V., Nabel, J. E. M. S., Poulter, B., Tian, H., Walker, A. P., and Zaehle, S.: Sources of uncertainty in regional and global terrestrial CO 2 exchange estimates, Global Biogeochemical Cycles, 34, e2019GB006393, https://doi.org/10.1029/2019GB006393, 2020b.

Becker, M., Olsen, A., Landschützer, P., Omar, A., Rehder, G., Rödenbeck, C., and Skjelvan, I.: The northern European shelf as an increasing net sink for CO2, Biogeosciences, 18, 1127–1147, https://doi.org/10.5194/bg-18-1127-2021, 2021.

Berchet, A., Sollum, E., Thompson, R. L., Pison, I., Thanwerdas, J., Broquet, G., Chevallier, F., Aalto, T., Berchet, A., Bergamaschi, P., Brunner, D., Engelen, R., Fortems-Cheiney, A., Gerbig, C., Groot Zwaaftink, C. D., Haussaire, J.-M., Henne, S., Houweling, S., Karstens, U., Kutsch, W. L., Luijkx, I. T., Monteil, G., Palmer, P. I., van Peet, J. C. A., Peters, W., Peylin, P., Potier, E., Rödenbeck, C., Saunois, M., Scholze, M., Tsuruta, A., and Zhao, Y.: The Community Inversion Framework v1.0: a unified system for atmospheric inversion studies, Geosci. Model Dev., 14, 5331–5354, https://doi.org/10.5194/gmd-14-5331-2021, 2021.

Boersma, K.F and , van Geffen, G. and Eskes, H. and van der A, R. and De Smedt, I. and Van Roozendael, M. and Yu, H. and Richter, A. and Peters, E. and Beirle, S. and Wagner, T. and Lorente, A. and Scanlon, T. and Compernoelle, S. and Lambert, J.-C.: Product Specification Document for the QA4ECV NO2 ECV precursor product, techreport QA4ECV Deliverable D4.6, http://www.qa4ecv.eu/sites/default/files/D4.6.pdf, 2017.

BP: 60 Years BP Statistical Review of World Energy: 1951–2011, available at: https://www.bp.com/en/global/corporate/ energy-economics/statistical-review-of-world-energy/downloads.html (last access: 8 February 2019), 2011.

BP: BP Statistical Review of World Energy June 2018, available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html, (last access: 14 June 2018).

BP: Methodology for calculating CO2 emissions from energy use, available at: https://www.bp.com/en/global/corporate/ energy-economics/statistical-review-of-world-energy/co2-emissions.html (last access: 8 February 2019), 2017.

Bradbury, N. J., Whitmore, A. P., Hart, P. B. S., and Jenkinson, D. S.: Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat, J. Agr. Sci., 121, 363-379, doi:10.1017/S0021859600085567, 1993.

Brophy, K., Graven, H., Manning, A. J., White, E., Arnold, T., Fischer, M. L., Jeong, S., Cui, X., and Rigby, M.: Characterizing uncertainties in atmospheric inversions of fossil fuel CO2 emissions in California, Atmos. Chem. Phys., 19, 2991–3006, https://doi.org/10.5194/acp-19-2991-2019, 2019.

Broquet, G., Chevallier, F., Rayner, P., Aulagnier, C., Pison, I., Ramonet, M., Schmidt, M., Vermeulen, A. T., and Ciais, P.: A European summertime CO2 biogenic flux inversion at mesoscale from continuous in situ mixing ratio measurements, J. Geophys. Res., 116, D23303, doi:10.1029/2011JD016202, 2011.

Broquet, G., Chevallier, F., Bréon, F.-M., Kadygrov, N., Alemanno, M., Apadula, F., Hammer, S., Haszpra, L., Meinhardt, F., Morguí, J. A., Necki, J., Piacentino, S., Ramonet, M., Schmidt, M., Thompson, R. L., Vermeulen, A. T., Yver, C., and Ciais, P.: Regional inversion of CO2 ecosystem fluxes from atmospheric measurements: reliability of the uncertainty estimates, Atmos. Chem. Phys., 13, 9039–9056, https://doi.org/10.5194/acp-13-9039-2013, 2013.

CDIAC, https://energy.appstate.edu/CDIAC (last access: 10 November 2022).

Ceccherini, G, Duveiller, G, Grassi, G, Lemoine, G, Avitabile, V, Pilli, R, and Cescatti, A.: Abrupt increase in harvested forest area over Europe after 2015, Nature, 583, 72–77, https://doi.org/10.1038/s41586-020-2438-y, 2020.

CEDS v_2019_12_23, https://www.pnnl.gov/projects/ceds (last access: 10 November 2022).

Chang, J., Ciais, P., Herrero, M., Havlik, P., Campioli, M., Zhang, X., Bai, Y., Viovy, N., Joiner, J., Wang, X., Peng, S., Yue, C., Piao, S., Wang, T., Hauglustaine, D. A., Soussana, J.-F., Peregon, A., Kosykh, N., and Mironycheva-Tokareva, N.: Combining livestock production information in a process-based vegetation model to reconstruct the history of grassland management, Biogeosciences, 13, 3757–3776, https://doi.org/10.5194/bg-13-3757-2016, 2016.

Chevallier, F., Fisher, M., Peylin, P., Serrar, S., Bousquet, P., Bréon, F.-M., Chédin, A., and Ciais, P.: Inferring CO2 sources and sinks from satellite observations: Method and application to TOVS data, J. Geophys. Res., 110, D24309, doi:10.1029/2005JD006390, 2005.

Chevallier, F., F.-M. Bréon, F.-M., and Rayner, P. J.: Contribution of the Orbiting Carbon Observatory to the estimation of CO2 sources and sinks: Theoretical study in a variational data assimilation framework, J. Geophys. Res., 112, D09307, doi:10.1029/2006JD007375, 2007.

Chevallier, F., Ciais, P., Conway, T. J., Aalto, T., Anderson, B. E., Bousquet, P., Brunke, E. G., Ciattaglia, L., Esaki, Y., Fröhlich, M., Gomez, A. J., Gomez-Pelaez, A. J., Haszpra, L., Krummel, P., Langenfelds, R., Leuenberger, M., Machida, T., Maignan, F., Matsueda, H., Morguí, J. A., Mukai, H., Nakazawa, T., Peylin, P., Ramonet, M., Rivier, L., Sawa, Y., Schmidt, M., Steele, P., Vay, S. A., Vermeulen, A. T., Wofsy, S., and Worthy, D. : CO2 surface fluxes at grid point scale estimated from a global 21-year reanalysis of atmospheric measurements. J. Geophys. Res., 115, D21307, doi:10.1029/2010JD013887, 2010.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer Chr., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T. and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437, 529–533, https://doi.org/10.1038/nature03972, 2005.

Ciais, P., Crisp, D., Denier van der Gon, H., Engelen, R., Janssens-Maenhout, G., Heimann, M., Rayner, P., and Scholze, M.: Towards a European Operational Observing System to Monitor Fossil CO2 emissions - Final Report from the expert group, https://www.copernicus.eu/sites/default/files/2019-09/CO2_Blue_report_2015.pdf, 2015.

Ciais, P., Yao, Y., Gasser, T., Baccini, A., Wang, Y., Lauerwald, R., Peng, S., Bastos, A., Li, W., Raymond, P.A. and Canadell, J.G., Peters, G. P., Andres, R. J., Chang, J., Yue, C., Dolman, A. J., Haverd, V., Hartmann, J., Laruelle, G., Konings, A. G., King, A. W., Liu, Y., Luyssaert, S., Maignan, F., Patra, P. K., Peregon, A., Regnier, P., Pongratz, J., Poulter, B., Shvidenko, A., Valentini, R., Wang, R., Brouquet, G., Yin, Y., Zscheischler, J., Guenet, B., Goll, D. S., Ballantyne, A.-P., Yang, H., Qiu, C., and Zhu, D.: Empirical estimates of regional carbon budgets imply reduced global soil heterotrophic respiration, National Science Review, 8, nwaa145, https://doi.org/10.1093/nsr/nwaa145, 2021.

CoCO2: https://coco2-project.eu/, last access: 21 November 2022.

Coleman, K., Jenkinson, D. S.: RothC-26.3 - A model the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU (ed) Evaluation of soil organic matter models using existing long-term datasets, NATO ASI Series I, vol. 38. Springer, Berlin, pp 237–246, 1996.

Crippa, M., Oreggioni, G., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J.G.J., and Vignati, E.: Fossil CO2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-11100-9, doi:10.2760/687800, JRC117610, 2019.

Deeter, M. N., Martínez-Alonso, S., Edwards, D. P., Emmons, L. K., Gille, J. C., Worden, H. M., Pittman, J. V., Daube, B. C., and Wofsy, S. C. (2013), Validation of MOPITT Version 5 thermal-infrared, near-infrared, and multispectral carbon monoxide profile retrievals for 2000–2011, J. Geophys. Res. Atmos., 118, 6710– 6725, doi:10.1002/jgrd.50272.

Deeter, M. N., Edwards, D. P., Francis, G. L., Gille, J. C., Mao, D., Martínez-Alonso, S., Worden, H. M., Ziskin, D., and Andreae, M. O.: Radiance-based retrieval bias mitigation for the MOPITT instrument: the version 8 product, Atmos. Meas. Tech., 12, 4561–4580, https://doi.org/10.5194/amt-12-4561-2019, 2019.

Deng, Z., Ciais, P., Tzompa-Sosa, Z. A., Saunois, M., Qiu, C., Tan, C., Sun, T., Ke, P., Cui, Y., Tanaka, K., Lin, X., Thompson, R. L., Tian, H., Yao, Y., Huang, Y., Lauerwald, R., Jain, A. K., Xu, X., Bastos, A., Sitch, S., Palmer, P. I., Lauvaux, T., d'Aspremont, A., Giron, C., Benoit, A., Poulter, B., Chang, J., Petrescu, A. M. R., Davis, S. J., Liu, Z., Grassi, G., Albergel, C., Tubiello, F. N., Perugini, L., Peters, W., and Chevallier, F.: Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions, Earth Syst. Sci. Data, 14, 1639–1675, https://doi.org/10.5194/essd-14-1639-2022, 2022.

Ducoudré, N. I., Laval, K., and Perrier, A.: SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land-atmosphere interface within the LMD atmospheric general circulation model, Journal of Climate, 6, 248– 273, https://www.jstor.org/stable/26197219, 1993.

ESA: Land Cover CCI Product User Guide Version 2. ESA. http://maps.elie.ucl.ac.be/CCI/viewer/index.php, (last access: 10 November 2022), 2017.

Eskes, H., et al: https://data-portal.s5p-pal.com/product-docs/no2/PAL_reprocessing_NO2_v02.03.01_20211215.pdf, 2021.

EU: REGULATION (EU) No 525/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change and repealing Decision No 280/2004/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0525&from=EN, 2013.

EU: Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG, 2018a.

EU: Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018R0842, 2018b.

EU: Communication COM/2020/562: Stepping up Europe’s 2030 climate ambition Investing in a climate-neutral future for the benefit of our people, https://knowledge4policy.ec.europa.eu/publication/communication-com2020562-stepping-europe%E2%80%99s-2030-climate-ambition-investing-climate_en, (last access: 10 November 2022), 2020.

EU: Procedure 2021/0201/COD, COM (2021) 554: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review, https://eur-lex.europa.eu/procedure/EN/2021_201, 2021a.

EU: Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119, 2021b.

EU NIR: Annual European Union greenhouse gas inventory 1990–2019 and inventory report 2021, Submission to the UNFCCC Secretariat, EEA/PUBL/2021/066, 2021.

EU NIR: Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022, Submission to the UNFCCC Secretariat, EEA/PUBL/2022/023, 2022.

Federici, S., Tubiello, F. N., Salvatore, M., Jacobs, H., and Schmidhuber, J.: New estimates of CO2 forest emissions and removals: 1990–2015, Forest Ecol. Manage., 352, 89–98, https://doi.org/10.1016/j.foreco.2015.04.022, 2015.

Feng, L., Palmer, P. I., Parker, R. J., Deutscher, N. M., Feist, D. G., Kivi, R., Morino, I., and Sussmann, R.: Estimates of European uptake of CO2 inferred from GOSAT XCO2 retrievals: sensitivity to measurement bias inside and outside Europe, Atmos. Chem. Phys., 16, 1289–1302, https://doi.org/10.5194/acp-16-1289-2016, 2016.

Fortems-Cheiney, A., Pison, I., Broquet, G., Dufour, G., Berchet, A., Potier, E., Coman, A., Siour, G., and Costantino, L.: Variational regional inverse modeling of reactive species emissions with PYVAR-CHIMERE-v2019, Geosci. Model Dev., 14, 2939–2957, https://doi.org/10.5194/gmd-14-2939-2021, 2021.

Fortems-Cheiney, A and Broquet, G.: D2.12: Final re-analysis of the national scale CO2 anthropogenic emissions over 2005-2015, https://projectsworkspace.eu/sites/VERIFY/Deliverables/WP2/VERIFY_D2.12_Final%20re-analysis%20of%20the%20national%20scale%20CO2%20anthropogenic%20emissions%20over%202005-2015_v1.pdf, 2021.

FRA: Global Forest Resources Assessment 2015: How are the world's forest changing?, 2015, Rome, Italy, available at: http: //www.fao.org/3/a-i4793e.pdf (last access: 10 December 2019), 2015.

Frey, H.C.: Evaluation of an Approximate Analytical Procedure for Calculating Uncertainty in the Greenhouse Gas Version of the Multi-Scale Motor Vehicle and Equipment Emissions System, Prepared for Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, MI, May 30, 2003.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., Arneth, A., Arora, V. K., Bates, N. R., Becker, M., Bellouin, N., Bittig, H. C., Bopp, L., Chevallier, F., Chini, L. P., Cronin, M., Evans, W., Falk, S., Feely, R. A., Gasser, T., Gehlen, M., Gkritzalis, T., Gloege, L., Grassi, G., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Jain, A. K., Jersild, A., Kadono, K., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lindsay, K., Liu, J., Liu, Z., Marland, G., Mayot, N., McGrath, M. J., Metzl, N., Monacci, N. M., Munro, D. R., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pan, N., Pierrot, D., Pocock, K., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Rodriguez, C., Rosan, T. M., Schwinger, J., Séférian, R., Shutler, J. D., Skjelvan, I., Steinhoff, T., Sun, Q., Sutton, A. J., Sweeney, C., Takao, S., Tanhua, T., Tans, P. P., Tian, X., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G. R., Walker, A. P., Wanninkhof, R., Whitehead, C., Willstrand

Wranne, A., Wright, R., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J., and Zheng, B.: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

Ganzenmüller, R., Bultan, S., Winkler, K., Fuchs, R., Zabel, F., and Pongratz, J.: Land-use change emissions based on high-resolution activity data substantially lower than previously estimated: Environmental Research Letters, 17, 64050, DOI 10.1088/1748-9326/ac70d8, 2022.

Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R. A., Ciais, P., and Obersteiner, M.: Historical CO2 emissions from land use and land cover change and their uncertainty, Biogeosciences, 17, 4075–4101, https://doi.org/10.5194/bg-17-4075-2020, 2020.

Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Vi nas, R. A., Alkama, ., Arneth, A., Bondeau, A., Dentener, F., Fader, M., Federici, S., Friedlingstein, P., Jain, A. K., Kato, E., Koven, C. D., Lee, D., Nabel, J. E. M. S., Nassikas, A. A., Perugini, L., Rossi, S., Sitch, S., Viovy, N., Wiltshire, A., and Zaehle, S.: Reconciling global-model estimates and country reporting of anthropogenic forest CO2 sinks, Nat. Clim. Chang., 8, 914–920, https://doi.org/10.1038/s41558-018-0283-x, 2018a.

Grassi, G., Pilli, R., House, J., Federici, S., and Kurz, W. A.: Science-based approach for credible accounting of mitigation in managed forests, Carbon balance Manag., 13, 8, https://doi.org/10.1186/s13021-018-0096-2, 2018b.

Grassi, G., Cescatti, A., Matthews, R., Duveiller, G., Amia, A., Federici, S., House, J., de Noblet-Ducoudré, N., Pilli, R., and Vizzarri, M.: On the realistic contribution of European forests to reach climate objectives, Carbon balance Manag., 14, 8, https://doi.org/10.1186/s13021-019-0123-y, 2019.

Grassi, G., Conchedda, G., Federici, S., Abad Viñas, R., Korosuo, A., Melo, J., Rossi, S., Sandker, M., Somogyi, Z., Vizzarri, M., and Tubiello, F. N.: Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting, Earth Syst. Sci. Data, 14, 4643–4666, https://doi.org/10.5194/essd-14-4643-2022, 2022a.

Grassi, G., Schwingshackl, C., Gasser, T., Houghton, R. A., Sitch, S., Canadell, J. G., Cescatti, A., Ciais, P., Federici, S., Friedlingstein, P., Kurz, W. A., Sanz Sanchez, M. J., Abad Viñas, R., Alkama, R., Ceccherini, G., Kato, E., Kennedy, D., Knauer, J., Korosuo, A., McGrath, M. J., Nabel, J., Poulter, B., Rossi, S., Walker, A. P., Yuan, W., Yue, X., and Pongratz, J.: Mapping land-use fluxes for 2001–2020 from global models to national inventories, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2022-245, in review, 2022b.

Hansis, E., Davis, S. J., and Pongratz, J.: Relevance of methodological choices for accounting of land use change carbon fluxes, Glob. Biogeochem. Cy., 29, 1230–1246, https://doi.org/10.1002/2014GB004997, 2015.

Hartung, K., Bastos, A., Chini, L., Ganzenmüller, R., Havermann, F., Hurtt, G. C., Loughran, T., Nabel, J. E. M. S., Nützel, T., Obermeier, W. A., and Pongratz, J.: Bookkeeping estimates of the net land-use change flux – a sensitivity study with the CMIP6 land-use dataset, Earth Syst. Dynam., 12, 763–782, https://doi.org/10.5194/esd-12-763-2021, 2021.

Harris, I., Osborn, T.J., Jones, P., and Lister, D.: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset, Sci Data 7, 109, https://doi.org/10.1038/s41597-020-0453-3, 2020.

Hastie, A., Lauerwald, R., Ciais, P., and Regnier, P. : Aquatic carbon fluxes dampen the overall variation of net ecosystem productivity in the Amazon basin: An analysis of the interannual variability in the boundless carbon cycle, Global Change Biology, 25 (6), pp. 2094-2111, DOI: 10.1111/gcb.14620, 2019.

Haverd, V., Smith, B., Cook, G. D., Briggs, P. R., Nieradzik, L., Roxburgh, S. H., Liedloff, A., Meyer, C. P., and Canadell, J. G.: A stand-alone tree demography and landscape structure module for Earth system models, Geophysical Research Letters, 40, 5234-5239, https://doi.org/10.1002/grl.50972, 2013.

Haverd, V., Smith, B., Nieradzik, L., Briggs, P. R., Woodgate, W., Trudinger, C. M., Canadell, J. G., and Cuntz, M.: A new version of the CABLE land surface model (Subversion revision r4601) incorporating land use and land cover change, woody vegetation demography, and a novel optimisation-based approach to plant coordination of photosynthesis, Geosci. Model Dev., 11, 2995–3026, https://doi.org/10.5194/gmd-11-2995-2018, 2018.

Houghton, R., Hobbie, J., Melillo, J., Moore, B., Peterson, B., Shaver, G., and Woodwell, G.: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO2 to the atmosphere, Ecol. Monogr., 53, 235–262, https://doi.org/10.2307/1942531, 1983.

Houghton, R. A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, Tellus B, 55, 378–390, https://doi.org/10.3402/tellusb.v55i2.16764, 2003.

Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C., and Ramankutty, N.: Carbon emissions from land use and land-cover change, Biogeosciences, 9, 5125–5142, https://doi.org/10.5194/bg-9-5125-2012, 2012.

Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover change 1850–2015, Glob. Biogeochem. Cy., 31, 456–472, https://doi.org/10.1002/2016GB005546, 2017.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020, 2020.

IPCC: Good Practice Guidance for Land use, Land use Change and Forestry, Chapter 3, 3.3, https://www.ipcc-ggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_FULL.pdf, (last access: 10 January 2022), 2003.

IPCC: Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, https://www.ipcc-nggip.iges.or.jp/public/2006gl/, 2006, (last access: 10 January 2022), 2006.

IPCC: Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, available at: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories, (last access: 10 January 2022), 2019.

IPCC: Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, edited by: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T. G., IPCC, Switzerland, 2014.

IPCC: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)].Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001, 2021.

Izaurralde, R. C., Williams, J. R., McGill, W. B., Rosenberg, N.J., and Jakas, M. C. Q.: Simulating soil C dynamics with EPIC: Model description and testing against long-term data, Ecol. Model. 192, 362–384, https://doi.org/10.1016/j.ecolmodel.2005.07.010, 2006.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J. G. J., Peters, J. A. H. W., van Aardenne, J. A., Monni, S., Doering, U., Petrescu, A. M. R., Solazzo, E., and Oreggioni, G. D.: EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012, Earth Syst. Sci. Data, 11, 959-1002, https://doi.org/10.5194/essd-11-959-2019, 2019.

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J.A., Fuchs, K., Guarin, J.R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A.K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E.J., Okada, M., Phillips, M., Porter, C., Rabin, S.S., Scheer, C., Schneider, J.M., Schyns, J.F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., and Rosenzweig, C.: Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat. Food, 2, 873–885, https://doi.org/10.1038/s43016-021-00400-y, 2021.

Jenkinson, D. S., Hart, P. B. S., Rayner, J. H., and Parry, L. C.: Modelling the turnover of organic matter in long-term experiments at Rothamsted, INTECOL Bulletin, 15, 1987.

Jenkinson, D. S., and Rayner, J. H.: The turnover of organic matter in some of the Rothamsted classical experiments, Soil. Sci., 123, 298–305, https://doi.org/10.1097/00010694-197705000-00005, 1977.

Jonsson, R., Blujdea, V. N., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., and Camia, A.: Outlook of the European forest-based sector: forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications, iForest, 11, 315–328, https://doi.org/10.3832/ifor2636-011, 2018.

Jonsson, R., Rinaldi, F., Pilli, R., Fiorese, G., Hurmekoski, E., Cazzaniga, N., Robert, N., and Camia, A: Boosting the EU forest-based bioeconomy: Market, climate, and employment impacts, Technological Forecasting and Social Change, 163, 120478, https://doi.org/10.1016/j.techfore.2020.120478, 2021.

Joos, F., Spahni, R., Stocker, B. D., Lienert, S., Müller, J., Fischer, H., Schmitt, J., Prentice, I. C., Otto-Bliesner, B., and Liu, Z.: N2O changes from the Last Glacial Maximum to the preindustrial – Part 2: terrestrial N2O emissions and carbon–nitrogen cycle interactions, Biogeosciences, 17, 3511–3543, https://doi.org/10.5194/bg-17-3511-2020, 2020.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S., Hnilo, J. J., Fiorino, M., and Potter, G. L.: NCEP–DOE AMIP-II Reanalysis (R-2). Bulletin of the American Meteorological Society, 83, 1631-1644, https://doi.org/10.1175/BAMS-83-11-1631, 2002.

Klein Goldewijk, K., Beusen, A., Doelman, J., and Stehfest, E.: Anthropogenic land-use estimates for the Holocene; HYDE 3.2, Earth Syst. Sci. Data, 9, 927–953, https://doi.org/10.5194/essd9-927-2017, 2017a.

Klein Goldewijk, K., Dekker, S. C., and van Zanden, J. L.: Percapita estimations of long-term historical land use and the consequences for global change research, J. Land Use Sci., 12, 313– 337, https://doi.org/10.1080/1747423X.2017.1354938, 2017b.

Koehl, M., Hildebrandt, R., Olschofsky, K., Koehler, R., Roetzer, T., Mette, T., Pretzsch, H., Koethke, M., Dieter, M., Abiy, M., Makeschin, F., and Kenter, B.: Combating the effects of climatic change on forests by mitigation strategies, Carbon Balance and Management, 5, 8, https://doi.org/10.1186/1750-0680-5-8, 2010.

Konovalov, I. B., Berezin, E. V., Ciais, P., Broquet, G., Zhuravlev, R. V., and Janssens-Maenhout, G.: Estimation of fossil-fuel CO2emissions using satellite measurements of "proxy" species, Atmos. Chem. Phys., 16, 13509–13540, https://doi.org/10.5194/acp-16-13509-2016, 2016.

Konovalov, I. B., and Lvova, D. A. : First, fast-track, Re-analysis of the national scale CO2 anthropogenic emissions over 2005-2015, internal VERIFY report: https://projectsworkspace.eu/sites/VERIFY/Deliverables/WP2/VERIFY_D2.10_First,%20fast-track,%20Re-analysis%20of%20the%20national%20scale%20CO2%20anthropogenic%20emissions%20over%202005-2015.pdf, (last access: 15 September 2020), 2018.

Kountouris, P., Gerbig, C., Rödenbeck, C., Karstens, U., Koch, T. F., and Heimann, M.: Technical Note: Atmospheric CO2 inversions on the mesoscale using data-driven prior uncertainties: methodology and system evaluation, Atmos. Chem. Phys., 18, 3027–3045, https://doi.org/10.5194/acp-18-3027-2018, 2018a.

Kountouris, P., Gerbig, C., Rödenbeck, C., Karstens, U., Koch, T. F., and Heimann, M.: Atmospheric CO2 inversions on the mesoscale using data-driven prior uncertainties: quantification of the European terrestrial CO2 fluxes, Atmos. Chem. Phys., 18, 3047–3064, https://doi.org/10.5194/acp-18-3047-2018, 2018b.

Krinner, G., Viovy, N., de Noblet-Ducoudré N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochemical Cycles, 19, GB1015, doi:10.1029/2003GB002199, 2005.

Kumarathunge, D. P., Medlyn, B. E., Drake, J. E., Tjoelker, M. G., Aspinwall, M. J., Battaglia, M., Cano, F. J., Carter, K. R., Cavaleri, M. A., Cernusak, L. A., Chambers, J. Q., Crous, K. Y., De Kauwe, M. G., Dillaway, D. N., Dreyer, E., Ellsworth, D. S., Ghannoum, O., Han, Q., Hikosaka, K., Jensen, A. M., Kelly, J. W. G., Kruger, E. L., Mercado, L. M., Onoda, Y., Reich, P. B., Rogers, A., Slot, M., Smith, N. G., Tarvainen, L., Tissue, D. T., Togashi, H. F., Tribuzy, E. S., Uddling, J., Vårhammar, A., Wallin, G., Warren, J. M. and Way, D. A.: Acclimation and adaptation components of the temperature dependence of plant photosynthesis at the global scale, New Phytologist, 222, 768-784, https://doi.org/10.1111/nph.15668, 2019.

Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw,C. H., Rampley, G. J., Smyth, C., Simpson, B. N., Neilson, E.T., Trofymow, J. A., Metsaranta, J., and Apps, M. J.: CBMCFS3: a model of carbon dynamics in forestry and land use change implementing IPCC standards, Ecol. Model., 220, 480–504, https://doi.org/10.1016/j.ecolmodel.2008.10.018, 2009.

Lauerwald, R., Laruelle, G. G., Hartmann, J., Ciais, P., and Regnier, P. A. G. :Spatial patterns in CO2 evasion from the global river network, Global Biogeochemical Cycles, 29, 534–554. https://doi.org/10.1002/2014GB004941015, 2015.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B., and Slater, A. G.: Parameterization Improvements and Functional and Structural Advances in Version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3, M03001, DOI 10.1029/2011MS000045, 2011.

Lienert, S. and Joos, F.: A Bayesian ensemble data assimilation to constrain model parameters and land-use carbon emissions, Biogeosciences, 15, 2909–2930, https://doi.org/10.5194/bg-15-2909-2018, 2018.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, Nat. Geosci., 2, 831–836, https://doi.org/10.1038/ngeo689, 2009.

Liski, J., Palosuo, T., Peltoniemi, M., and Sievänen, R.: Carbon and decomposition model Yasso for forest soils, Ecol. Model., 189, 168–182, https://doi.org/10.1016/J.ECOLMODEL.2005.03.005, 2005.

Liu, J., Baskaran, L., Bowman, K., Schimel, D., Bloom, A. A., Parazoo, N. C., Oda, T., Carroll, D., Menemenlis, D., Joiner, J., Commane, R., Daube, B., Gatti, L. V., McKain, K., Miller, J., Stephens, B. B., Sweeney, C., and Wofsy, S.: Carbon Monitoring System Flux Net Biosphere Exchange 2020 (CMS-Flux NBE 2020), Earth Syst. Sci. Data, 13, 299–330, https://doi.org/10.5194/essd-13-299-2021, 2021.

Lugato, E., Panagos, P., Bampa, F., Jones, A., Montanarella, L.: A new baseline of organic carbon stock in European agricultural soils using a modeling approach, Glob. Change Biol., 20, 313–326, https://doi.org/10.1111/gcb.12292, 2014.

Lurton, T., Balkanski, Y., Bastrikov, V., Bekki, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Contoux, C., Cozic, A., Cugnet, D., Dufresne, J.-L., Éthé, C., Foujols, M.-A., Ghattas, J., Hauglustaine, D., Hu, R.-M., Kageyama, M., Khodri, M., Lebas, N., Levavasseur, G., Marchand, M., Ottlé, C., Peylin, P., Sima, A., Szopa, S., Thiéblemont, R., Vuichard, N., and Boucher, O.: Implementation of the CMIP6 Forcing Data in the IPSL-CM6A-LR Model. Journal of Advances in Modeling Earth Systems, 12(4), e2019MS001940, https://doi.org/10.1029/2019MS001940, 2020.

Luyssaert, S., Abril, G., Andres, R., Bastviken, D., Bellassen, V., Bergamaschi, P., Bousquet, P., Chevallier, F., Ciais, P., Corazza, M., Dechow, R., Erb, K.-H., Etiope, G., Fortems-Cheiney, A., Grassi, G., Hartmann, J., Jung, M., Lathière, J., Lohila, A., Mayorga, E., Moosdorf, N., Njakou, D. S., Otto, J., Papale, D., Peters, W., Peylin, P., Raymond, P., Rödenbeck, C., Saarnio, S., Schulze, E.-D., Szopa, S., Thompson, R., Verkerk, P. J., Vuichard, N., Wang, R., Wattenbach, M., and Zaehle, S.: The European land and inland water CO2, CO, CH4 and N2O balance between 2001 and 2005, Biogeosciences, 9, 3357–3380, https://doi.org/10.5194/bg-9-3357-2012, 2012.

Luyssaert, S., Marie, G., Valade, A., Chen, Y. Y., Njakou Djomo, S., Ryder, J., Otto, J., Naudts, K., Lansø, A. S., Ghattas, J., and McGrath, M. J.: Trade-offs in using European forests to meet climate objectives, Nature, 562, 259–262, https://doi.org/10.1038/s41586-018-0577-1, 2018.

Mason Earles, J., Yeh, S. and Skog, K: Timing of carbon emissions from global forest clearance, Nature Clim Change, 2, 682–685, https://doi.org/10.1038/nclimate1535, 2012.

McGrath, M. J., Petrescu, A. M. R., Peylin, P., Andrew, R. M., Matthews, B., Dentener, F., Balkovič, J., Bastrikov, V., Becker, M., Broquet, G., Ciais, P., Fortems, A., Ganzenmüller, R., Grassi, G., Harris, I., Jones, M., Knauer, J., Kuhnert, M., Monteil, G., Munassar, S., Palmer, P. I., Peters, G. P., Qiu, C., Schelhaas, M.-J., Tarasova, O., Vizzarri, M., Winkler, K., Balsamo, G., Berchet, A., Briggs, P., Brockmann, P., Chevallier, F., Conchedda, G., Crippa, M., Dellaert, S., Denier van der Gon, H. A. C., Filipek, S., Friedlingstein, P., Fuchs, R., Gauss, M., Gerbig, C., Guizzardi, D., Günther, D., Houghton, R. A., Janssens-Maenhout, G., Lauerwald, R., Lerink, B., Luijkx, I. T., Moulas, G., Muntean, M., Nabuurs, G.-J., Paquirissamy, A., Perugini, L., Peters, W., Pilli, R., Pongratz, J., Regnier, P., Scholze, M., Serengil, Y., Smith, P., Solazzo, E., Thompson, R. L., Tubiello, F. N., Vesala, T. and Walther, S.: Data for the consolidated European synthesis of CO2 emissions and removals for EU27 and UK: 1990-2020, https://doi.org/10.5281/zenodo.7365863, 2022.

Menut, L., Bessagnet, B., Khvorostyanov, D., Beekmann, M., Blond, N., Colette, A., Coll, I., Curci, G., Foret, G., Hodzic, A., Mailler, S., Meleux, F., Monge, J.-L., Pison, I., Siour, G., Turquety, S., Valari, M., Vautard, R., and Vivanco, M. G.: CHIMERE 2013: a model for regional atmospheric composition modeling, Geosci. Model Dev., 6, 981–1028, https://doi.org/10.5194/gmd-6-981-2013, 2013.

Messager, M. L., Lehner, B., Grill, G., Nedeva, I. and Schmitt, O.: Estimating the volume and age of water stored in global lakes using a geo-statistical approach, Nat. Commun., 7, 13603, doi:10.1038/ncomms13603, 2016.

Monteil, G., Broquet, G., Scholze, M., Lang, M., Karstens, U., Gerbig, C., Koch, F.-T., Smith, N. E., Thompson, R. L., Luijkx, I. T., White, E., Meesters, A., Ciais, P., Ganesan, A. L., Manning, A., Mischurow, M., Peters, W., Peylin, P., Tarniewicz, J., Rigby, M., Rödenbeck, C., Vermeulen, A., and Walton, E. M.: The regional European atmospheric transport inversion comparison, EUROCOM: first results on European-wide terrestrial carbon fluxes for the period 2006–2015, Atmos. Chem. Phys., 20, 12063–12091, https://doi.org/10.5194/acp-20-12063-2020, 2020.

Monteil, G., and Scholze, M.: Regional CO2 inversions with LUMIA, the Lund University Modular Inversion Algorithm, v1.0, Geoscientific Model Development, 14, 3383–3406, https://doi.org/10.5194/gmd-14-3383-2021, 2021.

Mueller, N., Gerber, J., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A.: Closing yield gaps through nutrient and water management, Nature, 490, 254–257, https://doi.org/10.1038/nature11420, 2012.

Muñoz-Sabater, J.: ERA5-Land hourly data from 1981 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI 10.24381/cds.e2161bac, (last access: 1 May 2021), 2019.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications, Earth Syst. Sci. Data, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Nabuurs, G, Lindner, M, Verkerk, H, Gunia, K, Deda, P, Michalak, R, and Grassi, G.: First signs of carbon sink saturation in European forest biomass, Nature Climate Change 3, 792-796, https://doi.org/10.1038/nclimate1853, 2013.

Nabuurs, G. J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., Lindner, M., and Ollikainen, M.: By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry, Forests, 8, 484, https://doi.org/10.3390/f8120484, 2017.

Nabuurs, G. J., Arets, E. J. M. M., and Schelhaas, M. J.: Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU, Carbon Balance Manag., 13, 18, https://doi.org/10.1186/s13021-018-0107-3, 2018.

Naegler, T.: Reconciliation of excess 14C-constrained global CO2 piston velocity estimates, Tellus B, 61, 372–384, https://doi.org/10.1111/j.1600-0889.2008.00408.x, 2009.

Naudts, K., Chen, Y., McGrath, M., Ryder, J., Valade, A., Otto, J., and Luyssaert, S.: Europe's forest management did not mitigate climate warming, Science, 351, 597–600, https://doi.org/10.1126/science.aad7270, 2016.

Niwa, Y., Fujii, Y., Sawa, Y., Iida, Y., Ito, A., Satoh, M., Imasu, R., Tsuboi, K., Matsueda, H., and Saigusa, N.: A 4D-Var inversion system based on the icosahedral grid model (NICAM-TM 4D-Var v1.0) – Part 2: Optimization scheme and identical twin experiment of atmospheric CO2 inversion, Geosci. Model Dev., 10, 2201–2219, https://doi.org/10.5194/gmd-10-2201-2017, 2017.

Oleson, K.: Technical Description of the Community Land Model (CLM). NCAR Technical Note. TN-478+STR. 10.5065/D6RR1W7M, 2010.

Petrescu, A. M. R., Peters, G. P., Janssens-Maenhout, G., Ciais, P., Tubiello, F. N., Grassi, G., Nabuurs, G.-J., Leip, A., Carmona-Garcia, G., Winiwarter, W., Höglund-Isaksson, L., Günther, D., Solazzo, E., Kiesow, A., Bastos, A., Pongratz, J., Nabel, J. E. M. S., Conchedda, G., Pilli, R., Andrew, R. M., Schelhaas, M.-J., and Dolman, A. J.: European anthropogenic AFOLU greenhouse gas emissions: a review and benchmark data, Earth Syst. Sci. Data, 12, 961–1001, https://doi.org/10.5194/essd-12-961-2020, 2020.

Petrescu, A. M. R., McGrath, M. J., Andrew, R. M., Peylin, P., Peters, G. P., Ciais, P., Broquet, G., Tubiello, F. N., Gerbig, C., Pongratz, J., Janssens-Maenhout, G., Grassi, G., Nabuurs, G.-J., Regnier, P., Lauerwald, R., Kuhnert, M., Balkovič, J., Schelhaas, M.-J., Denier van der Gon, H. A. C., Solazzo, E., Qiu, C., Pilli, R., Konovalov, I. B., Houghton, R. A., Günther, D., Perugini, L., Crippa, M., Ganzenmüller, R., Luijkx, I. T., Smith, P., Munassar, S., Thompson, R. L., Conchedda, G., Monteil, G., Scholze, M., Karstens, U., Brockmann, P., and Dolman, A. J.: The consolidated European synthesis of CO2 emissions and removals for the European Union and United Kingdom: 1990–2018, Earth Syst. Sci. Data, 13, 2363–2406, https://doi.org/10.5194/essd-13-2363-2021, 2021b.

Pilli, R., Grassi, G., Kurz, W. A., Moris, J. V., and Viñas, R. A.: Modelling forest carbon stock changes as affected by harvest and natural disturbances – II. EU-level analysis including land use changes, Carbon Balance and Management, 11, 20, https://doi.org/10.1186/s13021-016-0059-4, 2016.

Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G., and Cescatti, A.: The European forest sector: past and future carbon budget and fluxes under different management scenarios, Biogeosciences, 14, 2387–2405, https://doi.org/10.5194/bg-14-2387-2017, 2017.

Pilli, R., Alkama, R., Cescatti, A., Kurz, W. A., and Grassi, G.: The European forest carbon budget under future climate conditions and current management practices, Biogeosciences, 19, 3263–3284, https://doi.org/10.5194/bg-19-3263-2022, 2022.

Pinty B., Janssens-Maenhout, G., Dowell, M., Zunker, H., Brunhes, T., Ciais, P., Dee, D., Denier van der Gon, H., Dolman, H., Drinkwater, M., Engelen, R., Heimann, M., Holmlund, K., Husband, R., Kentarchos, A., Meijer, Y., Palmer, P., and Scholze, M.: An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support capacity - Baseline Requirements, Model Components and Functional Architecture, European Commission Joint Research Centre, EUR 28736 EN, doi: 10.2760/39384, 2017.

Pisso, I., Sollum, E., Grythe, H., Kristiansen, N. I., Cassiani, M., Eckhardt, S., Arnold, D., Morton, D., Thompson, R. L., Groot Zwaaftink, C. D., Evangeliou, N., Sodemann, H., Haimberger, L., Henne, S., Brunner, D., Burkhart, J. F., Fouilloux, A., Brioude, J., Philipp, A., Seibert, P., and Stohl, A.: The Lagrangian particle dispersion model FLEXPART version 10.4, Geosci. Model Dev., 12, 4955–4997, https://doi.org/10.5194/gmd-12-4955-2019, 2019.

Polcher, J., McAvaney, B., Viterbo, P., Gaertner, M.-A., Hahmann, A., Mahfouf, J.-F., Noilhan, J., Phillips, T., Pitman, A.J., Schlosser, C.A., Schulz, J.-P., Timbal, B., Verseghy D., and Xue, Y.: A proposal for a general interface between land-surface schemes and general circulation models, Global and Planetary Change, 19, 263-278, https://doi.org/10.1016/S0921-8181(98)00052-6, 1998.

Pongratz, J., Reick, C. H., Houghton, R. A., and House, J. I.: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dynam., 5, 177–195, https://doi.org/10.5194/esd-5-177-2014, 2014.

Pongratz, J., Schwingshackl, C., Bultan, S., Obermeier, W., Havermann, F., and Guo, S.: Land Use Effects on Climate: Current State, Recent Progress, and Emerging Topics. Curr Clim Change Rep, 7, 99–120, https://doi.org/10.1007/s40641-021-00178-y, 2021.

Pongratz, J., Reick, C., Raddatz, T., and Claussen, M.: A reconstruction of global agricultural areas and land cover for the last millennium, Global Biogeochemical Cycles, 22, https://doi.org/10.1029/2007GB003153, 2008.

Ramankutty, N., and Foley, J. A.: Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global biogeochemical cycles, 13, 997-1027, https://doi.org/10.1029/1999GB900046, 1999.

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., and Guth, P. : Global carbon dioxide emissions from inland waters, Nature, 503, 355–359, https://doi.org/10.1038/nature12760, 2013.

RECAPP2: https://www.globalcarbonproject.org/Reccap/index.htm, last access: 22 November 2022.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luyssaert, S., Andersson, A. J., Arndt, S., Arnosti, C., Borges, A. V., Dale, A. W., Gallego-Sala, A., Goddéris, Y., Goossens, N., Hartmann, J., Heinze, C., Ilyina, T., Joos, F., LaRowe, D. E., Leifeld, J., Meysman, F. J. R., Munhoven, G., Raymond, P. A., Spahni, R., Suntharalingam, P., and Thullner, M.: Anthropogenic perturbation of the carbon fluxes from land to ocean, Nature Geosci, 6, 597–607, https://doi.org/10.1038/ngeo1830, 2013.

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D. C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A., and Wattenbach, M.: Climate extremes and the carbon cycle, Nature, 500, 287-95, doi: 10.1038/nature12350, 2013.

Resplandy, L., Keeling, R.F., Rödenbeck, C. Stephens, B. B., Khatiwala, S., Rodgers, K. B., Long, M. C., Bopp, L., and Tans, P. P.: Revision of global carbon fluxes based on a reassessment of oceanic and riverine carbon transport, Nature Geosci, 11, 504–509, https://doi.org/10.1038/s41561-018-0151-3, 2018.

Rödenbeck, C.: Estimating CO2 sources and sinks from atmospheric mixing ratio measurements using a global inversion of atmospheric transport, Tech. Rep. 6, Max Planck Institute for Biogeochemistry, Jena, Germany, 2005.

Rödenbeck, C., Gerbig, C., Trusilova, K., and Heimann, M.: A two-step scheme for high-resolution regional atmospheric trace gas inversions based on independent models, Atmos. Chem. Phys., 9, 5331–5342, https://doi.org/10.5194/acp-9-5331-2009, 2009.

Rödenbeck, C., Bakker, D. C., Metzl, N., Olsen, A., Sabine, C., Cassar, N., Reum, F., Keeling, R. F. and Heimann, M.: Interannual sea–air CO2 flux variability from an observation-driven ocean mixed-layer scheme, Biogeosciences, 11, 4599-4613, https://doi.org/10.5194/bg-11-4599-2014, 2014.

Sallnäs, O.: A matrix model of the Swedish forest, Studia Forestalia Suecica, 183, 1-23, https://pub.epsilon.slu.se/4514/, 1990.

Scarlat, N, Martinov, M, and Dallemand, J.F.: Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use, Waste Manag, 10, 1889-97, doi: 10.1016/j.wasman.2010.04.016, 2010.

Scharnweber, T., Smiljanic, M., Cruz-García, R., Manthey, M., and Wilmking, M.: Tree growth at the end of the 21st century - the extreme years 2018/19 as template for future growth conditions, Environ. Res. Lett., 15, 074022, https://doi.org/10.1088/1748-9326/ab865d, 2020.

Schelhaas, M.-J., Nabuurs, G.-J., Verkerk, P.J., Hengeveld, G., Packalen, T., Sallnäs, O., Pilli, R., Grassi, G., Forsell, N., Frank, S., Gusti, M., and Havlik, P.: Forest Resource Projection Tools at the European Level. In: Barreiro, S., Schelhaas, M.-J., McRoberts, R.E., Kändler, G. (Eds.), Forest Inventory-based Projection Systems for Wood and Biomass Availability, Springer International Publishing, Cham, pp. 49-68, 2017.

Schelhaas, M. J., Hengeveld, G. M., Filipek, S., König, L., Lerink, B., Staristsky, I., de Jong, A., Sikkema, R., and Nabuurs, G. J.: Documentation of the EFISCEN Space model, in prep.

Seidl, R., Schelhaas, M. J., Rammer, W. and Verkerk, P. J.: Increasing forest disturbances in Europe and their impact on carbon storage, Nature Clim Change, 4, 806–810, https://doi.org/10.1038/nclimate2318, 2014.

Silva, J. P., Toland, J., Jones, W., Eldrige, J., Thorpe, E., O'Hara, E.: LIFE and Europe’s grasslands: Restoring a forgotten habitat, report by the European Commission, https://ec.europa.eu/environment/archives/life/publications/lifepublications/lifefocus/documents/grassland.pdf, (last access: 10 November 2022), 2008.

Simmonds, P., Palmer, P. I., Rigby, M., McCulloch, A., O'Doherty, S. G., and Manning, A. J.: Tracers for evaluating computational models of atmospheric transport and dispersion at regional to global scales, Atm. Env., 246, 118074, doi:10.1016/j.atmosenv.2020.118074, 2021.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, Atmos. Chem. Phys., 12, 7825-7865, doi:10.5194/acp-12-7825-2012, 2012.

Simpson, D., Bergström, R., Imhof, H., and Wind, P.: Updates to the emep/msc-w model, 2016-2017. In Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report 1/2017. The Norwegian Meteorological Institute, Oslo, Norway, 2017.

Simpson, D., Bergström, R., Tsyro, S., and Wind, P.: Updates to the EMEP MSC-W model, 2018- 2019. In Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report 1/2019. The Norwegian Meteorological Institute, Oslo, Norway, 2019.

Simpson, D., Gonzalez Fernandez, I. A., Segers, A., Tsyro, S., Valdebenito, A., and Wind, P.: Updates to the EMEP MSC-W model, 2021-2022. In Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report 1/2022. The Norwegian Meteorological Institute, Oslo, Norway, 2022.

De Smet, P. A. M., and Hettelingh, J.-P.: Intercomparison of Current European Land Use/Land Cover Databases, Status Report 2001 Coordination Center for Effects, RIVM Report 259101010, Bilthoven, Netherlands, pp. 41-52, 2001.

Smith, J. U., Bradbury, N. J., and Addiscott, T.M.: SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land, Agron J, 88, 38-43, https://doi.org/10.2134/agronj1996.00021962008800010008x, 1996.

Smith, J. U., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D. R., Richards, M. I., Hillier, J., Flynn, H. C., Wattenbach, M., Aitkenhead, M., Yeluripurti, J. B., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A. P., Falloon, P. and Smith, P.: Estimating changes in national soil carbon stocks using ECOSSE – a new model that includes upland organic soils. Part I. Model description and uncertainty in national scale simulations of Scotland, Climate Research, 45, 179-192, doi: 10.3354/cr00899, 2010a.

Smith, J .U., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D. R., Richards, M. I., Hillier, J., Flynn, H. C., Wattenbach, M., Aitkenhead, M., Yeluripurti, J. B., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A.P., Falloon, P. and Smith, P.: Estimating changes in national soil carbon stocks using

ECOSSE – a new model that includes upland organic soils. Part II Application in Scotland, Climate Research, 45, 193-205, doi: 10.3354/cr00902, 2010b.

Smith, B., Wärlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11, 2027–2054, https://doi.org/10.5194/bg-11-2027-2014, 2014.

Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M., and Janssens-Maenhout, G.: Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, Atmos. Chem. Phys., 21, 5655–5683, https://doi.org/10.5194/acp-21-5655-2021, 2021.

Thompson, R. L., Broquet, G., Gerbig, C., Koch, T., Lang, M., Monteil, G., Munassar, S., Nickless, A., Scholze, M., Ramonet, M., Karstens, U., van Schaik, E., Wu, Z. and Rödenbeck, C.: Changes in net ecosystem exchange over Europe during the 2018 drought based on atmospheric observations, Phil. Trans. R. Soc. B, 375, 20190512, http://dx.doi.org/10.1098/rstb.2019.0512, 2020.

Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., Lorenzo Seguini, L., Manfron, G., Lopez-Lozano, R., Baruth, B., van den Berg, M., Dentener, F., Ceglar, A., Chatzopoulos, T., and Zampieri, M.: The exceptional 2018 European water seesaw calls for action on adaptation, Earth's Future, 7, 652–663, https://doi.org/10.1029/2019EF001170, 2019.

UK NIR: UK Greenhouse Gas Inventory, 1990 to 2020, Annual Report for Submission under the Framework Convention on Climate Change, 978-0-9933975-8-5, 2022.

UNFCCC: Kyoto Climte Change Decision, available at: https://unfccc.int/process-and-meetings/conferences/past-conferences/kyoto-climate-change-conference-december-1997/decisions-kyoto-climate-change-conference-december-1997, (last access: 5 October 2020), 1997.

UNFCCC: Decision 24/CP.19 Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention, FCCC/CP/2013/10/Add.3, 2014.

UNFCCC: NGHGI 2021 NIR reports: National Inventory Submissions 2021, available at: https://unfccc.int/ghg-inventories-annex-i-parties/2021, (last access: 01 January 2022), 2022a.

UNFCCC: NGHGI 2021 CRFs, available at: https://unfccc.int/ghg-inventories-annex-i-parties/2021, (last access 01 March 2022), 2022b.

VERIFY: http://verify.lsce.ipsl.fr/, last access: 21 November 2022.

VERIFY-CoCO2 Synthesis Plots: http://webportals.ipsl.jussieu.fr/VERIFY/FactSheets/, last access: 12 May 2023.

van der Laan-Luijkx, I. T., van der Velde, I. R., van der Veen, E., Tsuruta, A., Stanislawska, K., Babenhauserheide, A., Zhang, H. F., Liu, Y., He, W., Chen, H., Masarie, K. A., Krol, M. C., and Peters, W.: The CarbonTracker Data Assimilation Shell (CTDAS) v1.0: implementation and global carbon balance 2001–2015, Geosci. Model Dev., 10, 2785–2800, https://doi.org/10.5194/gmd-10-2785-2017, 2017.

Verkerk, P. J., Schelhaas, M.-J., Immonen, V., Hengeveld, G., Kiljunen, J., Lindner, M., Nabuurs, G.-J., Suominen, T., and Zudin, S.: Manual for the European Forest Information Scenario model (EFISCEN 4.1), EFI Technical Report 99, European Forest Institute, 49 pp., 2016.

Viovy, N.: Interannuality and CO2 sensitivity of the SECHIBA-BGC coupled SVAT-BGC model, Physics and Chemistry of The Earth, 21, 489-497, https://doi.org/10.1016/S0079-1946(97)81147-0, 1996.

Vizzarri, M., Pilli, R., Korosuo, A., Blujdea, V. N. B., Rossi, S., Fiorese, G., Abad-Vinas, R., Colditz, R. R., and Grassi, G.: Setting the forest reference levels in the European Union: overview and challenges, Carbon Balance Manage, 16, 23, https://doi.org/10.1186/s13021-021-00185-4, 2021.

Vuichard, N., Messina, P., Luyssaert, S., Guenet, B., Zaehle, S., Ghattas, J., Bastrikov, V., and Peylin, P.: Accounting for carbon and nitrogen interactions in the global terrestrial ecosystem model ORCHIDEE (trunk version, rev 4999): multi-scale evaluation of gross primary production, Geosci. Model Dev., 12, 4751–4779, https://doi.org/10.5194/gmd-12-4751-2019, 2019.

Wang, Y.-P., and Leuning, R.: A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I: Model description and comparison with a multi-layered model, Agricultural and Forest Meteorology, 91, 89-111, https://doi.org/10.1016/S0168-1923(98)00061-6, 1998.

Wang, Y. P., Law, R. M., and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosciences, 7, 2261–2282, https://doi.org/10.5194/bg-7-2261-2010, 2010.

Wanninkhof, R.: Relationship between wind speed and gas exchange over the ocean revisited: Gas exchange and wind speed over the ocean, Limnol. Oceanogr.-Meth., 12, 351–362, https://doi.org/10.4319/lom.2014.12.351, 2014.

Williams, J. R.: The Erosion-Productivity Impact Calculator (EPIC) Model: A Case History, Philos. Trans. R. Soc. B Biol. Sci. 329, 421–428, https://doi.org/10.1098/rstb.1990.0184, 1990.

Winkler, K., Fuchs, R., Rounsevell, M. D. A., and Herold, M.: HILDA+ Global Land Use Change between 1960 and 2019. PANGAEA, https://doi.org/10.1594/PANGAEA.921846, 2020.

Winkler, K., Fuchs, R., Rounsevell, M. and Herold, M.: Global land use changes are four times greater than previously estimated, Nat Commun, 12, 2501, https://doi.org/10.1038/s41467-021-22702-2, 2021.

WMO: United in Science Report, available at: https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate, (last access: January 2022), 2021.

Yvon-Durocher, G., Caffrey, J., Cescatti, A., Dossena, M., del Giorgio, P., Gasol, J. M., Montoya, J. M., Pumpanen, J., Staehr, P. A., Trimmer, M., Woodward, G., and Allen, A. P.: Reconciling the temperature dependence of respiration across timescales and ecosystem types, Nature, 487, 472–476, https://doi.org/10.1038/nature11205, 2012.

Zhang, B., Tian, H., Lu, C., Dangal, S. R. S., Yang, J., and Pan, S.: Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling, Earth Syst. Sci. Data, 9, 667–678, https://doi.org/10.5194/essd-9-667-2017, 2017.

Zscheischler, J., Mahecha, M. D., Avitabile, V., Calle, L., Carvalhais, N., Ciais, P., Gans, F., Gruber, N., Hartmann, J., Herold, M., Ichii, K., Jung, M., Landschützer, P., Laruelle, G. G., Lauerwald, R., Papale, D., Peylin, P., Poulter, B., Ray, D., Regnier, P., Rödenbeck, C., Roman-Cuesta, R. M., Schwalm, C., Tramontana, G., Tyukavina, A., Valentini, R., van der Werf, G., West, T. O., Wolf, J. E., and Reichstein, M.: Reviews and syntheses: An empirical spatiotemporal description of the global surface–atmosphere carbon fluxes: opportunities and data limitations, Biogeosciences, 14, 3685–3703, https://doi.org/10.5194/bg-14-3685-2017, 2017.

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