

Review of McGrath et al., 2023, for publication in ESSD “The consolidated European synthesis of  $1$  CO<sub>2</sub> emissions and removals for EU27 and UK: 1990-2020” by John Miller

First, apologies to the authors for the time it’s taken me to review this. Also, I want to acknowledge that I was only able to review the paper through page 66.

General comments are below and specific line by line comments are embedded as notes in the accompanying .pdf.

### **General comments:**

This is a hugely impressive (and huge) piece of work. Generally, the writing, graphing, and interpretation are at a very high level. I hope that the acceptance of the general and specific comments below and embedded in attached .pdf will serve to further improve the paper.

A comment to the editor(s), mainly: As someone (like most scientists) who thinks of data as measurements/observations and thus distinct from model output (forward or inverse, bottom-up or top-down) and inventories, I’m not sure I agree that the best venue for these types of papers is ESSD.

Be that as it may, though, since this paper is being submitted to ESSD, I think the bar for transparency and accessibility for all the “data” (obs, models, inventories) should be set very high and represent best (and not necessarily common) practice. In particular, before this paper is accepted for publication, I think there needs to be clear and “one-step” links to freely available, time and space-resolved model output, and inputs, for both the terrestrial biosphere and atmospheric models as well as inventories (realizing that inventories are not often gridded). Along these lines, unless a special arrangement can be made allowing free accessibility to IEA data, the EIA-based emissions need to be removed from the paper. Detailed codes and/or methods also need to be made available to the reader. I don’t simply mean that a reference is provided to, for example, an ORCHIDEE methods paper, but rather that the ORCHIDEE (and variants thereof) code(s) need to be made accessible via GitHub or similarly accessible platforms. While I realize this will take substantial time and effort, I think this is the required corollary of thinking of these sources of information as “data” and thus publishing in ESSD. More generally, I’m a strong believer in maximum accessibility and transparency and feel that it’s important that our community continues to move more and more in this direction. Ultimately, this is an important aspect of democratizing science: a

reader should not have to know someone or “be in the club” to have unfettered access to the details behind published results (e.g., codes, inputs and gridded fluxes).

Some technical, yet still general comments:

1. In the presentation of an ensemble of fossil CO<sub>2</sub> estimates, I’m interested to know more about their independence. To what extent are the different estimates using similar activity data and/or emissions factors? This question bears directly on the use of an ensemble as a proxy for uncertainty estimation which is critical when trying to understand the extent to which bottom-up and top-down estimates are different. The same comment applies to inventories (and to a lesser extent models) of terrestrial biosphere fluxes. There is brief mention of this issue around line 1360 in the Appendix, but this needs to be elevated to the main text and expanded.
2. The definition of managed land is very important for comparing top-down and bottom-up TBM fluxes with national inventories, as is the correction of top-down fluxes for lateral carbon transport. I think it would help to explain early on how both of these issues need to be accounted for when comparing TD and BU (e.g., TBM) estimates to national inventories. I realize that in the case of managed land definitions, these are not necessarily easy to obtain, but I would expect that these maps are available for most if not all of the countries in the present study. Moreover, in the case of the US, at least, > 99% of the area of the 48 contiguous states are considered managed, making this a minor issue. Even a rough initial description of how much a complication this is in TD/BU comparison would be helpful. Regarding lateral fluxes, in addition to early presentation of the necessity for correcting for these fluxes to arrive at stock/reservoir changes (at least in the case of using NEE estimates), discussion of the uncertainty of lateral flux uncertainties would be helpful.
3. Relatedly, there is no mention of masks of managed lands being applied to TD or BU fluxes when comparing to the inventories. Can you confirm this and also discuss the possible uncertainties associated with not doing this?
4. Use of the word “natural” (line 108 and elsewhere). There are several issues here. First, in the carbon cycle community more generally, “natural” often refers to emissions and removal by oceans and the terrestrial biosphere. In the context of national inventories, though, terrestrial ecosystem sources and sinks over managed land are counted as anthropogenic, so this usage needs to be clarified. Second, and more generally, even in unmanaged lands (and the oceans), using “natural” in the post-industrial era is not appropriate. Given

that we exist in a world strongly affected by anthropogenic impacts on CO<sub>2</sub>, temperature and precipitation (and also O<sub>3</sub>, N deposition, etc.), even so-called “natural” terrestrial biosphere and oceanic fluxes have a strong human component, and at this point we need to be using precise language in the scientific literature that reflects this. Finally, even if there were no anthropogenic component to NEE or net ocean fluxes, the typical dichotomy is that between “natural” and “anthropogenic” fluxes. But what does it say about our worldview? Is *homo sapiens*, and even fossil fuels, not part of the natural world? They’re certainly not supernatural. One way to distinguish fluxes might be as terrestrial biospheric, oceanic, and fossil, with perhaps some distinction for “TB” fluxes over managed and unmanaged land.

5. Finally, I think a table or glossary of terms would be useful: e.g., class, sector, category; acronyms/abbreviations like NBE, LUC, LUCC, LULUCF, etc.

For **specific line by line comments** in the attached .pdf, yellow highlights generally represent scientific/technical comments and blue highlights represent language-related comments.



# 1 The consolidated European synthesis of CO<sub>2</sub> emissions and removals for 2 EU27 and UK: 1990-2020 3

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61

62 **Abstract**

63 Quantification of land surface-atmosphere fluxes of carbon dioxide (CO<sub>2</sub>) fluxes and their trends and  
64 uncertainties is essential for monitoring progress of the EU27+UK bloc as it strives to meet ambitious targets  
65 determined by both international agreements and internal regulation. This study provides a consolidated synthesis of  
66 fossil sources (CO<sub>2</sub> fossil) and **natural** sources and sinks over land (CO<sub>2</sub> land) using bottom-up (BU) and top-down  
67 (TD) approaches for the European Union and United Kingdom (EU27+UK), updating earlier syntheses (Petrescu et  
68 al., 2020, 2021b). Given the wide scope of the work and the variety of approaches involved, this study aims to answer  
69 essential questions identified in the previous syntheses and understand the differences between datasets, particularly  
70 for poorly characterized fluxes from **managed ecosystems**. The work integrates updated emission inventory data,  
71 process-based model results, data-driven sectoral model results, and inverse modeling estimates, extending the  
72 previous period 1990-2018 to the year 2020 to the extent possible. BU and TD products are compared with European  
73 National Greenhouse Gas Inventories (NGHGs) reported by Parties including the year 2019 under the United Nations  
74 Framework Convention on Climate Change (UNFCCC). The uncertainties of the EU27+UK NGHGI were evaluated  
75 using the standard deviation reported by the EU Member States following the guidelines of the Intergovernmental  
76 Panel on Climate Change (IPCC) and harmonized by gap-filling procedures. Variation in estimates produced with  
77 other methods, such as atmospheric inversion models (TD) or spatially disaggregated inventory datasets (BU),  
78 originate from within-model uncertainty related to parameterization as well as structural differences between models.  
79 By comparing NGHGs with other approaches, key sources of differences between estimates arise primarily in  
80 activities. System boundaries and emission categories create differences in CO<sub>2</sub> fossil datasets, while different land  
81 use definitions for reporting emissions from Land Use, Land Use Change and Forestry (LULUCF) activities result in  
82 differences for CO<sub>2</sub> land. The latter has important consequences for atmospheric inversions, leading to inversions  
83 reporting stronger sinks in vegetation and soils than are reported by the NGHGI.

84 **For CO<sub>2</sub> fossil emissions**, after harmonizing estimates based on common activities and selecting the most  
85 recent year available for all datasets, the UNFCCC NGHGI for the EU27+UK accounts for 3392 ± 49 Tg CO<sub>2</sub> yr<sup>-1</sup>  
86 (926 ± 13 Tg C yr<sup>-1</sup>), while eight other BU sources report a mean value of 3340 [3238,3401] [25th,75th percentile] Tg  
87 CO<sub>2</sub> yr<sup>-1</sup> (948 [937,961] Tg C yr<sup>-1</sup>). The sole top-down inversion of fossil emissions currently available accounts for  
88 3800 Tg CO<sub>2</sub> yr<sup>-1</sup> (1038 Tg C yr<sup>-1</sup>), a value **close to that** of the NGHGI, but for which uncertainty estimates are not  
89 yet available. **For the net CO<sub>2</sub> land fluxes**, during the most recent five-year period including the NGHGI estimates,  
90 the NGHGI accounted for -91 ± 32 Tg C yr<sup>-1</sup> while six other BU approaches reported a mean sink of -62 [-117,-49]  
91 Tg C yr<sup>-1</sup> and a 15-member ensemble of dynamic global vegetation models (DGVMs) reported -69 [-152,-5] Tg C yr<sup>-1</sup>  
92 <sup>1</sup>. The five-year mean of three TD regional ensembles combined with one non-ensemble inversion of -73 Tg C yr<sup>-1</sup>  
93 has a slightly smaller spread (0th-100th percentile of [-135,45] Tg C yr<sup>-1</sup>), and was calculated after removing land-  
94 atmosphere CO<sub>2</sub> fluxes caused by lateral transport of carbon (crops, wood trade **and inland waters**) resulting in  
95 increased agreement with the the NGHGI and bottom-up approaches. Results at the sub-sector level (Forestland,  
96 Cropland, Grassland) show generally good agreement between the NGHGI and sub-sector-specific models, but results  
97 for a **DGVM** are mixed. Overall, for both CO<sub>2</sub> fossil and net CO<sub>2</sub> land fluxes, we find current **independent** approaches



98 are consistent with the NGHGI at the scale of the EU27+UK. We conclude that CO<sub>2</sub> emissions from fossil sources  
99 have decreased over the past 30 years in the EU27+UK, while **large uncertainties on net uptake of CO<sub>2</sub> by the land**  
100 **surface prevent trend identification**. In addition, a gap on the order of 1000 Tg C yr<sup>-1</sup> between CO<sub>2</sub> fossil emissions  
101 and net CO<sub>2</sub> uptake by the land exists regardless of the type of approach (NGHGI, TD, BU), falling well outside all  
102 available estimates of uncertainties. **However, uncertainties in top-down approaches to estimate CO<sub>2</sub> fossil emissions**  
103 **remain uncharacterized and are likely substantial**. The data used to plot the figures are available at  
104 <https://doi.org/10.5281/zenodo.7365863>.

105

## 106 1. Introduction

107 Atmospheric concentrations of greenhouse gasses (GHGs) reflect a balance between emissions from both  
108 human activities and natural sources, and removals by the terrestrial biosphere, oceans, and atmospheric oxidation.  
109 Increasing levels of GHG in the atmosphere due to human activities have been the major driver of climate change  
110 since the pre-industrial period (IPCC, 2021). In 2020, GHG mole fractions reached record highs, with globally  
111 averaged mole fractions of 413.2 parts per million (ppm) for carbon dioxide (CO<sub>2</sub>), representing 149% of the pre-  
112 industrial level (WMO, 2021). The rise in CO<sub>2</sub> **concentrations** in recent decades is caused primarily by CO<sub>2</sub> emissions  
113 from fossil sources. Globally, fossil emissions in 2020 (excluding the cement carbonation sink) totalled  $9.5 \pm 0.5$  Gt  
114 C yr<sup>-1</sup> ( $34.8 \pm 1.8$  Gt CO<sub>2</sub> yr<sup>-1</sup>), with expectations to rise in 2021 as the world recovered from the first year of the  
115 Covid-19 pandemic (Friedlingstein et al., 2022). In contrast, global net CO<sub>2</sub> emissions from land use and land use  
116 change (**LULUC**, primarily deforestation) estimated from bookkeeping models and dynamic global vegetation models  
117 (DGVMs) were **estimated to have a small decreasing trend over the** past two decades, albeit with low confidence  
118 (Friedlingstein et al., 2022). This decrease, however, is almost an order of magnitude less than the growth in fossil  
119 emissions over the same period, and therefore the total fossil and net LULUC flux has still increased.

120 As all countries in the EU27+UK are Annex I Parties<sup>1</sup> to the United Nations Framework Convention on  
121 Climate Change (UNFCCC), they prepare and report national GHG emission inventories (NGHGIs) on an annual  
122 basis. These inventories contain annual timeseries of each country's GHG emissions from the 1990 base year<sup>2</sup> until  
123 two years before the year of reporting and were originally set to track progress towards their reduction targets under  
124 the Kyoto Protocol (UNFCCC, 1997). Annex I NGHGIs are reported according to the Decision 24/CP.19 of the  
125 UNFCCC Conference of the Parties (COP) which states that the national inventories *shall* be compiled using the  
126 methodologies provided in the *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). The 2006  
127 IPCC Guidelines provide methodological guidance for estimating emissions for well-defined sectors using national  
128 activity and available emission factors. Decision trees indicate the appropriate level of methodological sophistication

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<sup>1</sup> 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).

<sup>2</sup> 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).



129 (*Tiered methods*) based on the absolute contribution of the sector to the national GHG balance and the country's  
130 national circumstances (availability and resolution of national activity data and emission factors). Generally, Tier 1  
131 methods are based on global or regional default emission factors that can be used with aggregated activity data, while  
132 Tier 2 methods rely on country-specific factors and/or activity data at a higher category resolution. Tier 3 methods are  
133 based on more detailed process-level modeling or in some cases facility-level emission observations. Annex I Parties  
134 are furthermore required to estimate and report uncertainties in emissions (95 % confidence interval) following the  
135 2006 IPCC guidelines using, as a minimum requirement, the Gaussian error propagation method (approach 1). Annex  
136 I Parties are furthermore encouraged to use Monte-Carlo methods (approach 2) or a hybrid approach. Additional  
137 information on the NGHGs can be found in Appendix A1.

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

148 The work presented in this paper covers dozens of distinct datasets and models, in addition to the individual  
149 country submissions to the UNFCCC of the EU Member States and the UK. As Annex I Parties, the NGHGs of the  
150 EU Member States and the UK are consistent with the general guidance laid out in IPCC (2006) yet still differ in  
151 specific approaches, models, and parameters, in addition to definitional differences in the underlying system  
152 boundaries and activity datasets. A comprehensive investigation of detailed differences between all datasets is beyond  
153 the scope of this paper, though systematic analyses have been previously made for specific sectors (e.g. AFOLU<sup>3</sup> -  
154 Petrescu et al., 2020; previous synthesis to this work - Petrescu et al., 2021b; FAOSTAT versus UNFCCC NGHGs -  
155 Tubiello et al., 2021, Grassi et al., 2022a; UNFCCC versus bookkeeping models - Grassi et al., 2022b; and UNFCCC  
156 versus inversions - Deng et al., 2021) and by the Global Carbon Project CO<sub>2</sub> syntheses (e.g., Friedlingstein et al.,  
157 2022). Every year (time “*t*”) the Global Carbon Project (GCP) in its Global Carbon Budget (GCB) quantifies large-  
158 scale CO<sub>2</sub> budgets up to the previous year (“*t-1*”), bringing in information from global to large latitude bands, including  
159 various observation-based flux estimates from BU and TD approaches (Friedlingstein et al., 2022). The current  
160 manuscript, given the focus on a single region (“Europe”) with extensive data coverage, dives into more detail than  
161 the GCB, including sector-specific models related to LULUCF (e.g., Forest land, Grassland, Cropland) and making  
162 heavy use of the EU27+UK NGHGI **in an effort to build mutual trust in the various approaches**. Compared to Petrescu  
163 et al. (2021b), the current work updates datasets, methods, and uncertainties.

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<sup>3</sup> We refer here to AFOLU as defined by the IPCC AR5: Agriculture, Forestry and Other Land Use.



164 BU observation-based approaches used in the GCB rely heavily on statistical data combined with Tier 1 and  
165 Tier 2 approaches. In the current work, focusing on a region that is well-covered with data and models (EU27+UK),  
166 BU also refers to Tier 3 process-based models (see Sect. 2). At regional and country scales, systematic and regular  
167 comparison of these observation-based CO<sub>2</sub> flux estimates with reported fluxes under the UNFCCC is more difficult.  
168 Continuing our previous efforts within the European project VERIFY (VERIFY, 2022), the current study compares  
169 observation-based flux estimates of BU versus TD approaches and compares them with **NGHGI** for the EU27-UK  
170 bloc and five sub-regions. VERIFY also provides, as a first attempt, similar comparisons for all European countries  
171 (VERIFY Synthesis Plots, 2022). The methodological and scientific challenges to compare these different estimates  
172 have been partly investigated before (Pongratz et al., 2021, Grassi et al., 2018a, for LULUCF; Andrew, 2020, for  
173 fossil sectors) but such comparisons were not done in a systematic and comprehensive way, including both fossil and  
174 land-based CO<sub>2</sub> fluxes, before Petrescu et al. (2021b).

175 As Petrescu et al. (2021b) is the most comprehensive comparison of the NGHGI and research datasets  
176 (including both TD and BU approaches) for the EU27+UK to date, the focus of the current paper is on improvement  
177 of estimates in the most recent version in comparison with the previous one, including changes in the uncertainty  
178 estimates and identification of the knowledge gaps and added value for policy making. Official NGHGI emissions are  
179 compared with research datasets, including necessary harmonization of the latter on total emissions to ensure  
180 consistency. Differences and inconsistencies between emission estimates were analyzed, and recommendations were  
181 made towards future evaluation of NGHGI data. It is important to remember that, while NGHGIs include uncertainty  
182 estimates, the “uncertainty analysis should be seen, first and foremost, as a means to help prioritize national efforts to  
183 reduce the uncertainty of inventories in the future, and guide decisions on methodological choice” (Volume 1, Chapter  
184 3, IPCC, 2006) and were therefore not developed to enable comparisons between countries or other datasets. In  
185 addition, individual spatially disaggregated research emission datasets often lack quantification of uncertainty. Here,  
186 we focus on the mean value and various percentiles (0th, 25th, 75th, 100th) of different research products of the same  
187 type to get a first estimate of uncertainty (see Sect. 2). Not all models/inventories provided an update for v2021, and,  
188 therefore, for the non-updated datasets the previously published timeseries are shown.

189

## 190 2. CO<sub>2</sub> data sources and estimation approaches

191 The CO<sub>2</sub> emissions and removals in the EU27+UK estimated by inversions and anthropogenic emission  
192 inventories resolved at the source category level were analyzed. At the time of this work, data of CO<sub>2</sub> fossil emissions  
193 and **CO<sub>2</sub> land<sup>4</sup> emissions and removals** (Tables 1 and 2) covered the period from 1990 to 2020, with some of the data  
194 only available for shorter time periods. Since then, some datasets have been updated to include 2021, but not all, and

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<sup>4</sup> The IPCC Good Practice Guidance (GPG) for Land Use, Land Use Change and Forestry (IPCC, 2003) describes a uniform structure for reporting emissions and removals of greenhouse gasses. This format for reporting can be seen as “land based”: all land in the country must be identified as having remained in one of six classes since a previous survey, or as having changed to a different (identified) class in that period. According to IPCC **SRCCl**: Land covers the terrestrial portion of the biosphere that comprises the natural resources (soil, near surface air, vegetation and other biota, and water) the ecological processes, topography, and human settlements and infrastructure that operate within that system”. Some communities prefer “biogenic” to describe these fluxes, while others find this confusing as fluxes from unmanaged forests, for example, are “biogenic” but not included in inventories reported to the UNFCCC. **As this comparison is central to our work, we decided that “land” as defined by the IPCC was a good compromise.**





195 we made the decision to stay with the original time window for simplicity. The estimates are available both from  
196 peer-reviewed literature and from new research results from the VERIFY project. BU results are compared to NGHGI  
197 reported in 2021 (which contain the timeseries for 1990-2019). Data sources are summarized in Tables 1 and 2 with  
198 the detailed description of all products provided in Appendices A1-A2. In Appendix A, the harmonized methodology  
199 for calculation of uncertainties submitted by Member States to the UNFCCC in their National Inventory Reports  
200 (NIRs) is explained. This includes the same 95 % confidence interval as is typically reported, but involved an  
201 extensive gap-filling to cover more categories and more years than available in Petrescu et al. (2021b), which limited  
202 uncertainty estimation to a single year.

203 BU anthropogenic CO<sub>2</sub> fossil estimates include global inventory datasets such as the Emissions Database for  
204 Global Atmospheric Research (EDGAR v6.0.), Statistical Review of World Energy by BP, the Carbon Dioxide  
205 Information Analysis Center (CDIAC), the Global Carbon Project (GCP), the Energy Information Administration's  
206 (EIA) "International" dataset, and the International Energy Agency (IEA) (see Table 1). These datasets are all  
207 described in detail by Andrew (2020). CO<sub>2</sub> land emission estimates are derived from BU biogeochemical models (e.g.  
208 DGVMs, bookkeeping models, see Table 2). TD approaches include both high spatial resolution regional inversions  
209 (CarboScopeReg, EUROCOM (Monteil et al., 2020), inversions based on the CIF-CHIMERE system (Berchet et al.,  
210 2021) and LUMIA) and coarser spatial resolution global inversions (GCP 2021: Friedlingstein et al., 2022). Most of  
211 the inversions were carried out for CO<sub>2</sub> land emissions, with only a single inversion for CO<sub>2</sub> fossil emissions (CIF-  
212 CHIMERE). Note that CIF-CHIMERE provides estimates for both CO<sub>2</sub> land and CO<sub>2</sub> fossil from separate simulations.  
213 These estimates are described in Sect. 2.3.

214 The sign of the fluxes is defined from an atmospheric perspective: positive values represent a net source to  
215 the atmosphere and negative values a net removal from the atmosphere. As an overview of potential uncertainty  
216 sources, Table B1 presents the use of emission factor data (EF), activity data (AD), and, whenever available,  
217 uncertainty methods used for all CO<sub>2</sub> land data sources in this study, in addition to more details on each model in  
218 Appendices A. The referenced data used for the figures' replicability purposes are available for download (McGrath  
219 et al., 2022). Upon request, the codes necessary to plot the figures in the same style and layout can be provided. The  
220 focus is on EU27+UK emissions. In the VERIFY project, an additional web tool was developed which allows for the  
221 selection and display of all plots shown in this paper, not only for the EU Member States and UK but for a total of 79  
222 countries and groups of countries in Europe (Table A1, Appendix A). The data is free and can be accessed upon  
223 registration (VERIFY Synthesis Plots, 2022).

224 For the sake of harmonization, we report the mean values of all ensembles. For small sample sizes (e.g., the  
225 regional inversions of CSR with four members), the literature does not give a clear indication on whether the mean or  
226 the median is preferred; a preference for one or the other depends on what one wishes to demonstrate. In particular,  
227 the median downplays the skewness of the data (outliers). We have taken efforts to exclude outliers from the datasets  
228 used to construct ensembles, and consequently the datasets which remain should be randomly distributed. For this  
229 reason, we display the mean for all ensembles. As the number of datasets in some ensembles is small (less than five),  
230 we display the minimum and maximum annual values for every year (i.e., the 0th/100th percentiles) to give an idea  
231 of the spread. For ensembles with more than ten members (i.e., TRENDY), we show the mean and the 0th/100th



232 percentiles along with the 25th/75th percentiles in the figures. This combination demonstrates "more likely" and  
233 "possible" behavior; as only one ensemble has both bars, displaying them does not overwhelm the reader much more  
234 than the standard graphs, and we find the added information to be worth the trade-off. In the text, we report the mean  
235 and 0/100th percentiles for small ensembles and mean along with the 25th/75th for larger ensembles.

236 The current work extends Petrescu et al. (2021b) by updating the included datasets (both increasing the  
237 number of years covered and in some cases updating the model versions), adding datasets, and highlighting changes  
238 in terms of mean annual emissions and trends. For clarity, the data from Petrescu et al. (2021b) is labeled as v2019,  
239 while the latest results are labeled v2021.

240

## 241 2.1. CO<sub>2</sub> anthropogenic emissions from NGHGI

242 The UNFCCC NGHGI (2021) estimates for the period 1990 to year  $t-2$  (2019), collected for the EU27 and  
243 UK, are the basis for this dataset. For historical reasons, a few EU countries provide data for a different base year than  
244 1990<sup>5</sup>, yet it should be noted that regardless of the base year all countries of the EU27+UK bloc are obliged to report  
245 estimates for the period 1990 to year  $t-2$ . The Annex I Parties to the UNFCCC are required to report annual GHG  
246 inventories that include a NIR, with qualitative information on data and methods and a Common Reporting Format  
247 (CRF) set of tables that provide quantitative information on GHG emission by category. This annually updated dataset  
248 includes anthropogenic emissions and removals. For the land-based sector, the **land management proxy** is used as a  
249 way to report only anthropogenic fluxes (Grassi et al., 2018a, 2021). This proxy allows Member States to report all  
250 fluxes coming from land **designed** as "managed" without trying to disentangle their natural and anthropogenic origins.  
251 Figure B1 shows the annual NGHGI (2021) anthropogenic CO<sub>2</sub> timeseries disaggregated by sector in order to provide  
252 context.

253

## 254 2.2. CO<sub>2</sub> fossil emissions

255 CO<sub>2</sub> fossil emissions occur when fossil carbon compounds are broken down via combustion or other non-  
256 combustive industrial processes. Most of these fossil compounds are in the form of fossil fuels, such as coal, oil, and  
257 natural gas. Another source category of fossil CO<sub>2</sub> emissions is fossil carbonates, such as calcium carbonate and  
258 magnesium carbonate, which are used in industrial processes. Because CO<sub>2</sub> fossil emissions are largely connected  
259 with energy, which is a closely tracked commodity group of high economic importance, there is a wealth of underlying  
260 data that can be used for estimating emissions. However, differences in collection, treatment, interpretation and  
261 inclusion of various factors – such as carbon contents and fractions of the fuel's carbon that is oxidized – lead to  
262 methodological differences (Appendix A) resulting in differences of emissions between datasets (Andrew, 2020).  
263 Atmospheric inversions for emissions of fossil CO<sub>2</sub> are not as established as their bottom-up counterparts (Brophy et

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<sup>5</sup> 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).



264 al., 2019). The main reason is that the types of **atmospheric monitoring instruments** suitable for fossil CO<sub>2</sub> atmospheric  
265 inversions have not yet been widely deployed (Ciais et al., 2015). One of the rare inversions is presented below.

266 In this analysis, the inventory-based bottom-up CO<sub>2</sub> fossil emissions estimates are separated and presented  
267 per fuel type and reported for the last year when all data products are available (2017). This updates Andrew (2020)  
268 and Petrescu et al. (2021b) which both report the year 2014. In order to provide a quasi-independent estimate of fossil  
269 emissions assimilating satellite observations of the atmosphere, the CIF-CHIMERE model was used to produce a  
270 fossil fuel CO<sub>2</sub> emission estimate for the year 2017. CIF-CHIMERE is a coupling between the variational mode of  
271 the Community Inversion Framework (CIF) platform developed in the VERIFY project (Berchet et al., 2021), the  
272 CHIMERE chemistry transport model (Menut et al., 2013) and the adjoint of this model (Fortems-Cheiney et al.,  
273 2021a). To overcome the lack of CO<sub>2</sub> observation networks suitable for the monitoring of fossil fuel CO<sub>2</sub> emissions  
274 at national scale, this inversion is based on the assimilation of satellite NO<sub>2</sub> data, as NO<sub>2</sub> is co-emitted with CO<sub>2</sub> during  
275 fossil fuel combustion. Recent top-down inversions of anthropogenic CO<sub>2</sub> emissions from Europe indicate that  
276 uncertainties using satellite measurements of co-emitted NO<sub>2</sub> are much lower than for co-emitted CO when deriving  
277 fossil CO<sub>2</sub> emissions (Konovalov et al., 2016). Therefore, results shown below only incorporate NO<sub>2</sub> and not CO  
278 observations. While the spatial and temporal coverage of the NO<sub>2</sub> observations is large, there are many factors that  
279 determine the ratio of NO<sub>2</sub> to CO<sub>2</sub> emissions. Therefore, the influence of using NO<sub>2</sub> observations in determining fossil  
280 CO<sub>2</sub> emissions is subject to uncertainties which have not been characterized appropriately yet in the framework of  
281 VERIFY. Here, **this conversion relies heavily on the emission ratios per country**, month and large sector of activity  
282 from the TNO-GHGco-v3 inventory (Dellaert et al., 2021), which has been partly developed in VERIFY, and which  
283 is based on the most recent UNECE-CLRTAP<sup>6</sup> and UNFCCC official country reporting respectively for air pollutants  
284 and greenhouse gasses. The detailed descriptions of each of the data products are found in Appendix A1.

285

286 *Table 1: Data sources for the anthropogenic CO<sub>2</sub> fossil emissions included in this study, all updated from Petrescu et*  
287 *al. (2021b):*

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<sup>6</sup> UNECE Convention on Long-Range Transboundary Air Pollution. <https://unece.org/environment-policy/air>



Anthropogenic CO <sub>2</sub> fossil			
Data/model name	Contact / lab	Species / Period	Reference/Metadata
UNFCCC NGHGI (2021)	UNFCCC	Anthropogenic fossil CO <sub>2</sub> 1990-2019	IPCC (2006) UNFCCC NIRs/CRFs <a href="https://unfccc.int/ghg-inventories-annex-i-parties/2021">https://unfccc.int/ghg-inventories-annex-i-parties/2021</a> (UNFCCC, 2021a, 2021b)
Compilation of multiple CO <sub>2</sub> fossil emission data sources (Andrew 2020) EDGAR v6.0, BP, EIA, CDIAC, IEA, GCP, CEDS, PRIMAP	CICERO	CO <sub>2</sub> fossil country totals and split by fuel type 1990-2018 (or last available year)	EDGAR v6.0 <a href="https://edgar.jrc.ec.europa.eu/">https://edgar.jrc.ec.europa.eu/</a> BP 2021 report (BP, 2021) EIA <a href="https://www.eia.gov/beta/international/data/browser/views/partial/sources.html">https://www.eia.gov/beta/international/data/browser/views/partial/sources.html</a> CDIAC <a href="https://energy.appstate.edu/CDIAC">https://energy.appstate.edu/CDIAC</a> (Gilfillan and Marland, 2021) IEA : <a href="http://www.iea.org">www.iea.org</a> CEDS <a href="https://github.com/JGCRI/CEDS">https://github.com/JGCRI/CEDS</a> (O'Rourke et al., 2021) GCP (Friedlingstein et al., 2022) PRIMAP-hist (Gütschow et al., 2021) <a href="https://doi.org/10.5281/zenodo.4479171">https://doi.org/10.5281/zenodo.4479171</a>
Fossil fuel CO <sub>2</sub> inversions	LSCE	Inverse fossil fuel CO <sub>2</sub> emissions 2005-2020	Fortems-Cheiney et al. (2021) Fortems-Cheiney and Broquet (2021)

288 **2.3. CO<sub>2</sub> land fluxes**

289

290 Data products from BU and TD CO<sub>2</sub> land fluxes including CO<sub>2</sub> emissions and removals from land use, land  
 291 use change, and forestry (LULUCF) activities are summarized in Table 2. All models and approaches produce an  
 292 estimate of the net carbon flux from the land surface including uptake through photosynthesis and emission through  
 293 respiration and/or disturbances. The details may vary significantly between approaches, however. Attempts are made  
 294 where possible to harmonize input data and compare results which roughly correspond to similar categories included  
 295 in the NGHGI. Further details are described throughout the rest of this article. As with CO<sub>2</sub> fossil fluxes, the primary  
 296 distinctions are between the NGHGI, other bottom-up approaches, and top-down approaches. The situation becomes



297 more complicated for CO<sub>2</sub> land fluxes due to the inclusion of approaches which only address a single land use class  
298 (e.g., Forest land).

299 For the analysis at category level, the CO<sub>2</sub> net emissions from the LULUCF sector that are primarily  
300 considered in this synthesis are from three land use classes<sup>7</sup> (Forest land, Cropland, and Grassland), each split into a  
301 land class remaining in the same land class<sup>8</sup> or a land class converted to another class. The NGHGI are the only  
302 results discussed here which make use of this transition period, but the distinction is important so as to inform which  
303 NGHGI categories to use in the comparison. Wetlands, Settlements, Other land, and Harvested wood products (HWP)  
304 categories are included in the discussion on total LULUCF activities in Sect. 3.3.1, 3.3.3 and 3.3.4. Not all the classes  
305 reported to the UNFCCC are present in **FAOSTAT** or other models. Some models are sector-specific (e.g., Forest  
306 land) while other models include a larger subset of the six UNFCCC classes (e.g., DGVMs which simulate Forest  
307 land, Grassland, and Cropland). The notations FL, CL and GL are used to indicate total emissions and removals from  
308 the respective Forest land, Cropland and Grassland land use categories (i.e. the remaining + conversions to these  
309 classes). The notations “FL-FL”, “CL-CL” and “GL-GL” are used to indicate emissions and removals from respective  
310 forest, cropland and grassland areas which have remained in the same class from year to year, or in the case of NGHGI  
311 lands that have not undergone conversion within the aforementioned transition period (e.g. *t-20*).

312 The results from sector-specific models reporting carbon fluxes for FL-FL (EFISCEN-Space and CBM), CL  
313 and GL (EPIC-IIASA and ECOSSE) are presented separately from the models and datasets including multiple land  
314 use categories and simulating land use changes: FAOSTAT (version 2021), the DGVM ensemble TRENDY v10  
315 (Friedlingstein et al., 2022; Le Quéré et al., 2009), the ORCHIDEE and CABLE-POP DGVMs forced by high  
316 resolution meteorological data as part of the VERIFY project, and the two bookkeeping approaches of H&N  
317 (Houghton & Nassikas, 2017) and BLUE (Hansis et al., 2015). BLUE includes two simulations with different land-  
318 use forcing, one made for the VERIFY H2020 project and one for the GCP 2021 (Friedlingstein et al., 2022). For CL  
319 and GL both the EPIC-IIASA and ECOSSE sector-specific models reported updates, although ECOSSE only updated  
320 results for GL. **Process** included in all the products are summarized in Appendix A2 and Table B2.

321 **The** two updated inverse model ensembles presented are the GCP2021 for the period 2010-2020  
322 (Friedlingstein et al., 2022) and EUROCOM for the period 2009-2018 (Monteil et al., 2020; Thompson et al., 2020).  
323 The GCP inversions are global and include CarbonTracker Europe (CTE: van der Laan-Luijkx et al., 2017), CAMS  
324 (Chevallier et al., 2005), the Jena CarboScope (Rödenbeck, 2005), NIESMON-CO<sub>2</sub> (Niwa et al., 2017), CMS-Flux  
325 (Liu et al., 2021) and UoE (Feng et al., 2016). The EUROCOM inversions are regional, with a domain limited to  
326 Europe and higher spatial resolution atmospheric transport models, with four inversions covering the entire period  
327 2009-2018 as analyzed in Thompson et al. (2020). All inversions provide Net Ecosystem Exchange (NEE) fluxes.  
328 These inversions make use of more than 30 atmospheric observing stations within Europe, including flask data and

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<sup>7</sup> According to 2006 IPCC guidelines the LULUCF sector includes six management classes (Forest land, Cropland, Grassland, Wetlands, Settlements and Other land)

<sup>8</sup> According to 2006 IPCC guidelines, land converted to a new category should be reported in a “conversion” category for *N* years and then moved to a “remaining” category, unless a further change occurs. Converted land refers to CO<sub>2</sub> emissions from conversions to and from all six classes that occurred in the previous *N* years. By default, *N* is equal to 20, although the guidelines recognize that longer times may be necessary in temperate and boreal environments for the dead biomass and soil carbon pools to reach the new equilibrium. Member States have the freedom to select a length of time appropriate to their own circumstances.



329 continuous observations and work at typically higher spatial resolution than the global inversion models (Table 2).  
330 The **prior** anthropogenic emissions provided for all regional inversions reported here (i.e., EUROCOM, EUROCOM  
331 drought 2018, VERIFY CSR, VERIFY CIF-CHIMERE, and VERIFY LUMIA) are all based on EDGAR v4.3, BP  
332 statistics, and TNO datasets by generating spatial and temporal distributions through the COFFEE approach  
333 (Steinbach et al., 2011). **Small differences** exist between exact versions used by the different groups. The prior  
334 anthropogenic emissions for the GCP global inversions, GridFEDv2021 and v2022, are also based on EDGARv4.3.2  
335 (Janssens-Maenhout et al., 2019). Overall, differences in the prior anthropogenic emissions **are not expected to explain**  
336 **the large differences seen between the different regional biogenic inversions** nor between the regional and global  
337 biogenic inversions, but efforts should be continued to harmonize them to the greatest extent possible in future  
338 intercomparisons.

339 Additional inversions for Europe from three regional scale inversion systems are analyzed. Two of these  
340 systems are part of the EUROCOM ensemble, but new runs were carried out for the VERIFY project. The  
341 **CarboScopeRegional (CSR)** inversion system has performed additional runs for VERIFY for the years 2006-2020  
342 with multiple ensemble members differing by biogenic prior fluxes and assimilated observations. The results are  
343 plotted separately to illustrate two points: 1) that the CSR simulations for VERIFY are not identical to those submitted  
344 to EUROCOM (VERIFY runs from CSR included several sites that started shortly before the end of the EUROCOM  
345 inversion period), and 2) the CSR model was used in four distinct runs in VERIFY. Note that the ensemble members  
346 differ from previous years (the spatial correlation length is kept constant this year, while more prior fluxes are used).  
347 By presenting CSR separate from the EUROCOM results, one can get an idea of the uncertainty due to various model  
348 parameters in one inversion system with one single transport model. The LUMIA inversion system submitted four  
349 simulation results to the VERIFY project, based on the 2018 Drought Task Force project (labeled here as EUROCOM,  
350 Thompson et al., 2020). The primary difference is that the years 2019-2020 were added based on boundary conditions  
351 using **TM5 and ERA5** meteorological data. The four different variants include one reference simulation and three  
352 simulations which change spatial correlation lengths, the number of observation sites, and the magnitude of  
353 uncertainties in the boundary conditions. As one of the variants is only available for 2019-2020 (changing the  
354 uncertainties in the boundary conditions), this variant was dropped from the results and only the remaining three  
355 simulations are presented, covering the period 2006-2020.

356 An inversion of the NEE over 2005-2020 from the CIF-CHIMERE variational inversion system is also  
357 analyzed. The configuration of this inversion is close to that of the PYVAR-CHIMERE NEE inversions in the  
358 EUROCOM ensembles and follows the general principles of Broquet et al. (2013). However, it uses distinct inputs,  
359 which play a critical role in the inversion, such as a more recent ORCHIDEE simulation as prior estimate of the NEE  
360 and a more recent CAMS global inversion to impose the regional CO<sub>2</sub> boundary conditions.

361

362 *Table 2: Data sources for the land CO<sub>2</sub> emissions included in this study. Details are found in Appendix A2.*



NGHGI net CO <sub>2</sub> land flux				
Data source	Contact / lab	Variables Period (timestep) Resolution	References	Status compared to Petrescu et al. (2021b)
UNFCCC <b>NGHGI (2021)</b>	Member State inventory agencies  Annual uncertainty gap-filling for total LULUCF by <b>Environment Agency Austria (EAA)</b> .	LULUCF Net CO <sub>2</sub> emissions/removals. 1990-2019 ( <b>1Y</b> ) Country-level	IPCC (2006) UNFCCC CRFs  <a href="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">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</a>	Updated
Inventory and model estimates of net CO <sub>2</sub> land flux				
<b>ORCHIDEE</b>	LSCE	CO <sub>2</sub> fluxes from all ecosystems reported as <b>Net Biome Productivity (NBP)</b> . 1990-2020 ( <b>3H</b> ) 0.125° x 0.125°	Ducoudré et al. (1993) Viovy et al. (1996) Polcher et al. (1998) Krinner et al. (2005)	Updated
<b>CABLE-POP</b>	Western Sydney University	CO <sub>2</sub> fluxes (NBP). Model includes N cycling. 1990-2020 ( <b>1M</b> ) 0.125° x 0.125°	Haverd et al. (2018)	New
<b>TRENDY v10</b>	MetOffice UK	CO <sub>2</sub> fluxes (NBP) 15 models (all except ISAM) 1990-2020 ( <b>3H-1M</b> ) 0.125° x 0.125°	Friedlingstein et al. (2022; Table 4)	Updated



<b>CO<sub>2</sub> emissions from inland waters</b>	ULB	Average C fluxes from rivers, lakes and reservoirs, with lateral C transfer from soils. 1990-2018 (-) 0.1° x 0.1°	Lauerwald et al. (2015) Hastie et al. (2019) Raymond et al. (2013)	Not updated
<b>CBM</b>	EC-JRC	CO <sub>2</sub> fluxes (NBP) as historical 2000-2015 and extrapolation for 2017-2020 (1Y) Country-level	Kurz et al. (2009) Pilli et al. (2022)	Updated
<b>ECOSSE</b>	UNIABDN	CO <sub>2</sub> 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)	Updates only for croplands
<b>EFISCEN-Space</b>	WUR	CO <sub>2</sub> 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)	Updates for 15 countries
<b>EPIC-IIASA</b>	IIASA	CO <sub>2</sub> fluxes (NBP) from cropland 1991-2020 (1M) 0.125° x 0.125°	Balkovič et al. (2013, 2018, 2020) Izaurrealde et al. (2006) Williams et al. (1990)	Updated for croplands, new estimates for grasslands
<b>BLUE (VERIFY) and BLUE (GCP)</b>	LMU Munich	CO <sub>2</sub> 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	Updated
<b>H&amp;N</b>	Woodwell Climate Research Center	CO <sub>2</sub> fluxes from land use change. 1990-2020 (1Y) Country-level	Houghton and Nassikas (2017)	Updated
<b>FAO</b>	FAOSTAT	CO <sub>2</sub> emissions / removal from LULUCF processes. 1990-2020 (1Y) Country-level	FAO (2021) Federici et al. (2015) Tubiello et al. (2021)	Updated
<b>CO<sub>2</sub> atmospheric inversion estimates</b>				





<b>CSR inversions for VERIFY</b>	MPI -Jena	Total CO <sub>2</sub> inverse flux (NBP) 2006-2020 (3H) 0.5° x 0.5°	Kountouris et al. (2018 a,b)	Updated
<b>LUMIA</b>	Lund University (INES)	Total CO <sub>2</sub> inverse flux (NBP) 2006-2020 (1W) 0.25° x 0.25°	Monteil and Scholze (2021)	New
<b>CIF-CHIMERE</b>	LSCE	Total CO <sub>2</sub> inverse flux (NBP) 2005-2020 (3H) 0.5° x 0.5°	Berchet et al. (2021) Broquet et al. (2013)	New
<b>GCP 2021 global inversions (CTE, CAMS, CarboScope, NISMON-CO<sub>2</sub>, UoE, CMS-Flux)</b>	GCP	Total CO <sub>2</sub> inverse flux (NBP) Six inversions 2010-2020 (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
<b>EUROCOM regional inversions (CSR, LUMIA, PYVAR)</b>	LSCE, ULUND, MPI-Jena, NILU	Total CO <sub>2</sub> inverse flux (NBP) Three inversions 2009-2018 (3H-1M)	Monteil et al. (2020) Thompson et al. (2020)	Updated (also replaced CSR with the mean of the four runs submitted to VERIFY). FLEXINVERT and NAME are not included (Fig. A5)

363

364 All of the bottom-up models in this work require external forcing datasets. In the context of the VERIFY  
 365 project (VERIFY, 2022), an effort was made to provide a single, harmonized version of several kinds of data  
 366 (meteorological, land use/land cover, and nitrogen deposition) on a high-resolution grid over Europe. These datasets  
 367 were then made available to all of the modeling groups to use in their simulations. Such a practice is common in  
 368 model intercomparison projects. However, as the models in Table 2 are not all the same type, data harmonization  
 369 presented more of a challenge in this work as not all models use the same inputs. All of the datasets described in  
 370 Appendix A2 were used by at least one modeling group in this work.

### 371 3. Results and discussion

#### 372 3.1. Overall NGHGI reported anthropogenic CO<sub>2</sub> fluxes

373 In 2019, the UNFCCC NGHGI (2021) net CO<sub>2</sub> flux estimates for EU27+UK, accounted for 3.01 Gt CO<sub>2</sub>  
 374 from all sectors (including LULUCF) and 3.28 Gt CO<sub>2</sub> excluding LULUCF (Fig. B1), corresponding to a net sink of



375 LULUCF of  $-0.27 \pm 0.11$  Gt CO<sub>2</sub>. In 2019, few large economies accounted for the majority of EU27+UK emissions,  
376 with Germany, UK, Italy and France representing 53 % of the total CO<sub>2</sub> emissions (excluding LULUCF). For the  
377 LULUCF sector, the countries reporting the largest CO<sub>2</sub> sinks in 2019 were Italy, Spain, Sweden, and France  
378 accounting for 56 % of the overall EU27+UK sink. Only a few countries (Czech Republic, The Netherlands, Ireland  
379 and Denmark) reported a net LULUCF source in 2019. Some countries, like Portugal, report sources in some years  
380 due to wildfires, with sinks in other years. The NGHGI shows minimal inter-annual variability (largely due to  
381 methodology), and consequently the 2019 values are indicative of longer-term averages, showing a constant trend  
382 between 2017-2019.

383 CO<sub>2</sub> fossil emissions reported by Member States are dominated by the energy sector (energy combustion and  
384 fugitives) representing 92 % of the total EU27 + UK CO<sub>2</sub> emissions (excluding LULUCF) or 3.02 Gt CO<sub>2</sub> yr<sup>-1</sup> in 2019.  
385 The Industrial Process and Product Use (IPPU) sector contributes 7.6 % or 0.2 Gt CO<sub>2</sub> yr<sup>-1</sup>. CO<sub>2</sub> emissions reported  
386 as part of the agriculture sector cover only liming and urea application, UNFCCC categories 3G and 3H<sup>9</sup> respectively.  
387 Together with waste, in 2019 the emissions from agriculture represent 0.4 % of the total UNFCCC CO<sub>2</sub> emissions in  
388 the EU27+UK.

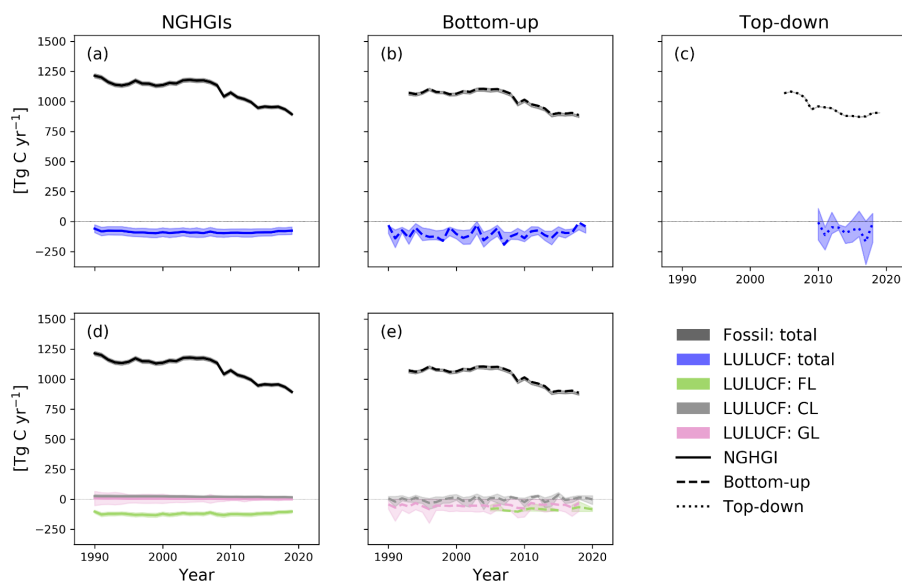
389 An overview of all CO<sub>2</sub> fossil and land datasets in this work (Fig. 1) leads to a series of conclusions: 1)  
390 Regardless of the method used (NGHGI, bottom-up models, top-down models), the timeseries of annual fluxes from  
391 fossil CO<sub>2</sub> emissions rest almost one order of magnitude higher than removals from CO<sub>2</sub> uptake/removal by the land  
392 surface and well outside uncertainty estimates; 2) Uncertainties are much larger in the LULUCF estimates than in the  
393 fossil CO<sub>2</sub> estimates (both for total LULUCF and for individual components of FL, CL, and GL); 3) Interannual  
394 variability (IAV) is much more present in non-NGHGI LULUCF datasets than in NGHGI LULUCF datasets or any  
395 of the fossil datasets.

396 The overall message that fossil CO<sub>2</sub> emissions exceed the land sink (Fig. 1a-c) is the same as found in the  
397 Global Carbon Budget (Friedlingstein et al., 2022), although the difference is larger in the EU27+UK. Contrary to  
398 the GCB, however, fossil CO<sub>2</sub> emissions in the EU27+UK have decreased over the past three decades. Again, this  
399 finding is supported by the NGHGI, bottom-up models, and a single atmospheric inversion. Similarly, carbon uptake  
400 by the land surface has remained more or less stable over the past three decades, with the vast majority of that occurring  
401 in forests. While the latter conclusion is clear in the NGHGI (Fig. 1d), very large spreads among bottom-up sectorial  
402 models lead to more uncertainty (bottom-center).

403 The difference in uncertainty between the estimates of fossil CO<sub>2</sub> emissions and CO<sub>2</sub> uptake/removal by the  
404 land surface is also striking. Eight bottom-up models produce a 25-75 % percentile which is almost invisible on the  
405 scale of the graph (center-top, gray shading). On the other hand, four models estimating Grassland emissions/removals  
406 produce an error bar that covers the bottom part of the graph and masks any apparent trend (bottom-center, light green  
407 shading). A similar conclusion can be drawn from top-down estimates of LULUCF fluxes (top-right, blue shading).  
408 Additional work on reducing the uncertainty of LULUCF fluxes in the EU27+UK is highly welcome.  
409

---

<sup>9</sup> 3G and 3H refer to UNFCCC category activities, as reported by the standardized common reporting format (CRF) tables, which contain CO<sub>2</sub> emissions from agricultural activities: liming and urea applications.



410  
411 *Figure 1: A synthesis of all the CO<sub>2</sub> net fluxes shown in the work for the EU27+UK. The estimates are divided by*  
412 *approach: NGHGI estimates (panels a, d); bottom-up methods (b, e); and top-down methods (c). Panels (d) and (e)*  
413 *include a breakdown of the LULUCF flux into three of the dominant components: FL, GL, and CL. Such a breakdown*  
414 *is not provided for NGHGI CO<sub>2</sub> fossil as partitioning of bottom-up CO<sub>2</sub> fossil datasets corresponding to UNFCCC*  
415 *NGHGI categories is not currently available. The NGHGI UNFCCC uncertainty is calculated for submission year*  
416 *2021 as the relative error of the NGHGI value, computed with the 95 % confidence interval method gap-filled and*  
417 *provided for every year of the timeseries, except for FL, GL, and CL which are taken directly from the EU NIR (2021).*  
418 *Shaded areas for the other estimates represent the 0th-100th percentiles for groups with fewer than seven members,*  
419 *and the 25th-75th percentile for groups with seven or more members. Ensembles (e.g., TRENDY v10) are included*  
420 *in the above **only their mean values**, to avoid more heavily weighting the ensembles compared to the other datasets.*  
421

422 Several caveats remain with this overall synthesis. First, the timeseries were combined rather naively in Fig. 1  
423 by taking the mean of annual timeseries for each dataset discussed below. This leads to, for example, the 15-member  
424 TRENDY ensemble being given identical weight as the ORCHIDEE high-resolution simulation over Europe. This  
425 was done to weigh more heavily the regional approaches under **the assumption** that higher resolution simulations and  
426 more region-specific input data will lead to more accurate results. While the latter assumption appears reasonable,  
427 **the first assumption can be disputed**. Second, only a single top-down result for fossil CO<sub>2</sub> emissions is currently  
428 available, preventing an estimate of the uncertainty for this approach. Third, sector models were combined  
429 disregarding distinctions between those models estimating **“Remain” and “Total”** fluxes. These points are discussed



430 in more detail in the following sections. However, addressing these points is highly unlikely to alter the overall  
431 conclusions in this section.

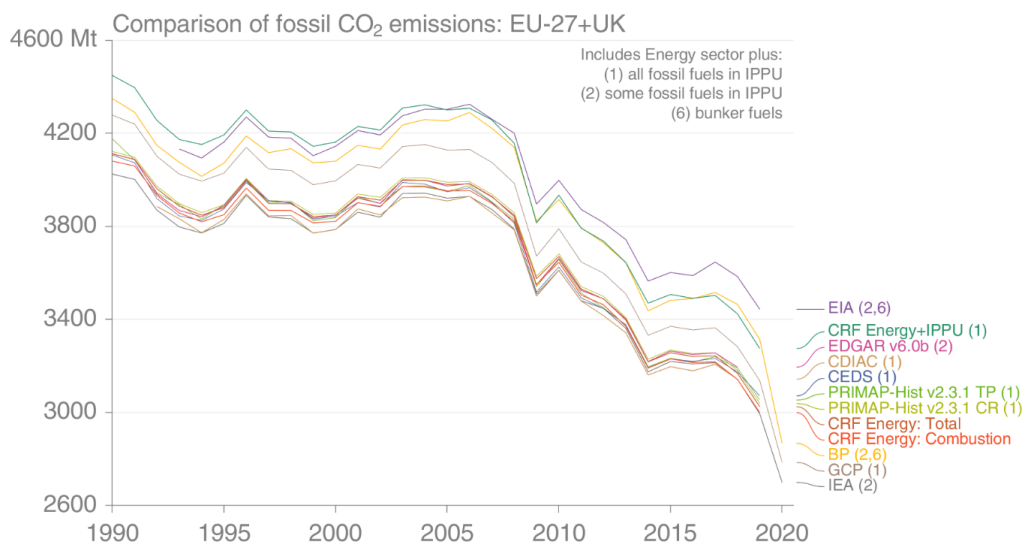
432

### 433 3.2. CO<sub>2</sub> fossil emissions

434 The inventory-based fossil CO<sub>2</sub> estimates from nine data sources (and some subsets) are presented as timeseries  
435 (1990-last available year) based on Andrew (2020) with the objective to explore differences between datasets and  
436 visualize trends (Fig. 2). Because the emissions source coverage (also called the “system boundary”) of datasets  
437 varies, comparing total emissions from these datasets is not a like-for-like comparison. Therefore, some harmonization  
438 of system boundaries prior to comparison is needed. This harmonization relies on specifying the system boundary of  
439 each dataset and, where possible, removing emission sources to produce a near-common system boundary. For  
440 example, if IEA doesn't include any carbonates, then carbonates are removed from all emissions datasets that report  
441 these separately. UNFCCC (CRFs) Energy+IPPU, CDIAC, CEDS, PRIMAP, and GCP include Energy sector plus  
442 all fossil fuels in IPPU; EIA, EDGAR and BP include some fossil fuels in IPPU, while EIA and BP include bunker  
443 fuels as well. UNFCCC CRFs include Energy total and Energy combustion. Further details on how data sets are  
444 harmonized are provided by Andrew (2020). Because of differing levels of detail provided by datasets, it isn't possible  
445 to do this perfectly, but the approximate harmonization gives something closer to a like-for-like comparison, with the  
446 legend in Fig. 2 indicating the most significant remaining differences. The pre-harmonization curves are shown in  
447 Appendix A (Fig. A1) for reference.

448

449



450



451 **Figure 2:** Comparison of EU27+UK fossil CO<sub>2</sub> emissions from multiple inventory datasets with system boundaries  
452 harmonized as much as possible. Harmonization is limited by the disaggregated information presented by each  
453 dataset. CDIAC does not report emissions prior to 1992 for former-Soviet Union countries. CRF: UNFCCC NGHGI  
454 from the Common Reporting Format tables. The pre-harmonization figure is shown in Fig. A1.

455 Given the remaining differences in system boundaries after harmonization, most datasets agree well  
456 (Andrew, 2020). In response to inconsistencies identified in this work, the EIA recently corrected some double-  
457 counting of emissions from liquid fuels and has revised its estimates of total emissions down about 10 % for the  
458 EU27+UK (pers. comm., US Energy Information Agency, February 2022). For comparison, applying a similar  
459 harmonization procedure to the UNFCCC NGHGI and retaining only Fuel combustion (1A), Fugitive emissions (1B),  
460 Chemical industry (2B), Metal industry (2C), Non-energy products from fuels and solvent use (2D), and Other (2H)  
461 results in emissions of  $3392 \pm 49$  Tg CO<sub>2</sub> yr<sup>-1</sup> ( $926 \pm 13$  Tg C yr<sup>-1</sup>) for the year 2017, where the uncertainty was  
462 propagated through quadrature using the gap-filled uncertainties described in this work and taking the total sector  
463 uncertainty if the category uncertainty was not available. This mean value falls within the 25th-75th percentiles of  
464 the eight other harmonized BU sources ([3238,3401] Tg CO<sub>2</sub> yr<sup>-1</sup>).

465 The sole available inversion for CO<sub>2</sub> fossil fluxes is produced by the CIF-CHIMERE model, shown in Fig.  
466 1c and Fig. B3 (for a single year). The inversion yields plausible and **consistent** fossil emission estimates compared  
467 to nine bottom-up estimates from BU datasets with global coverage (Fig. 1b,c,B3). Uncertainties of CIF-CHIMERE  
468 inversion estimate have not yet been quantified, **however they are likely largely driven by large uncertainties in the**  
469 **input data**. The satellite observations of NO<sub>2</sub> have large uncertainties, which partly explains the small departure from  
470 the prior fluxes during the optimization. Emission ratios between NO<sub>2</sub> and CO<sub>2</sub> are also uncertain (those from the prior  
471 are currently used). The **atmospheric residence time** of NO<sub>2</sub> is another major source of uncertainty. The inversion  
472 reports total fossil CO<sub>2</sub> emissions calculated from **NO<sub>x</sub>** combustion emissions. However, in principle, the derivation  
473 of CO<sub>2</sub> emissions from the NO<sub>x</sub> inversions should be restricted to fossil fuel CO<sub>2</sub> emissions based on the fossil fuel  
474 CO<sub>2</sub>/NO<sub>x</sub> ratio from the TNO, as there is a **better**-established relationship between CO<sub>2</sub> and NO<sub>x</sub> from combustion of  
475 fossil fuels. **Future inversions co-assimilating CO<sub>2</sub> data will make a clearer distinction in the processing of fossil-fuel**  
476 **and other anthropogenic emissions**. Finally, it's important to note that the inversion results are not fully independent  
477 of the bottom-up methods, **as the prior estimates are based on TNO gridded products**. However, part of the lack of  
478 departure from the prior can also be attributed to the general consistency between the prior and the observations, which  
479 raise optimistic perspectives for the co-assimilation of co-emitted species with the data from future CO<sub>2</sub> networks  
480 dedicated to anthropogenic emissions.

481

482

483

### 484 **3.3. CO<sub>2</sub> land fluxes**

485 This section updates the benchmark data collection of CO<sub>2</sub> emissions and removals from the LULUCF sector  
486 in EU27+UK previously published in Petrescu et al. (2020) and Petrescu et al. (2021b), expanding on the scope of  
487 those works by adding additional datasets and years. The countries analyzed in this study use country-specific activity



488 data and emissions factors for the most important land use categories and pools (EU NIR 2022, UK NIR 2022).  
489 However, several gaps still exist, mainly in non-forest lands and **non-biomass pools** (e.g., EU NIR, 2022). In addition,  
490 since NGHGs largely rely on periodic forest inventories (carried out every five to ten years) for the most important  
491 land use (Forest land), the net CO<sub>2</sub> LULUCF flux often does not capture the most recent changes, nor the full  
492 interannual variability.

493 While the net LULUCF CO<sub>2</sub> flux was relatively stable from 1990 to 2016, staying mostly between -300 to -  
494 350 Mt CO<sub>2</sub>/yr, in the past three years the sink has weakened to around -250 Mt CO<sub>2</sub>/yr in 2020 (black dotted line in  
495 Fig. B2, Appendix B; Abad-Viñas, pers. comm, 2022). This weakening occurred mostly in Forest land, due to a  
496 combination of increased natural disturbances, forest aging and increased wood demand (Nabuurs et al., 2013; EU  
497 NIR, 2022). Natural disturbances, including fires (especially in the southern Mediterranean), windthrows, droughts  
498 and insect infestations (especially in central and northern European countries), have increased in recent years (e.g.,  
499 Seidl et al., 2014) which explains most of the interannual variability of NGHGs. **Forest aging** affects the net sink  
500 both through the forest growth (net increment) - which tends to level off or decline after a certain age - and the harvest,  
501 because a greater area of forest reaches forest maturity (Grassi et al., 2018b). Although the exact increase in total  
502 harvest in Europe in recent years is still subject to debate (Ceccherini et al., 2020; Palahi et al. et al., 2021), demand  
503 for fuelwood at least has increased (Camia et al., 2021).

504 Carbon uptake as seen by the atmosphere may occur on either managed or unmanaged land, **and results from**  
505 **processes such as photosynthesis, respiration, and disturbances (e.g., fire, pests, harvest)**. As discussed by Petrescu et  
506 al. (2020), the fluxes reported in NGHGs relate to emissions and removals from direct LULUCF activities (clearing  
507 of vegetation for agricultural purposes, regrowth after agricultural abandonment, wood harvesting and recovery after  
508 harvest and management) but also indirect CO<sub>2</sub> fluxes due to processes such as responses to **environmental drivers** on  
509 managed land. Additional CO<sub>2</sub> fluxes occur on unmanaged land, **but these fluxes are very small in Europe**. According  
510 to Table 4.1 in the EU27 and UK NGHGs (2021) CRF, almost all land (~95 %) in the EU27+UK is considered  
511 managed. France and Greece report some unmanaged forest areas (1.1 % and 16.6 %, respectively). Hungary and  
512 Malta report unmanaged **Grassland** areas of 33 % and 100 %, respectively, and Nordic and Baltic countries plus  
513 Ireland, Slovakia and Romania report sometimes quite large (up to 100 %) unmanaged wetland areas.

514 The indirect CO<sub>2</sub> fluxes on managed and unmanaged land due to changing climate, increasing atmospheric  
515 carbon dioxide concentrations, and nitrogen deposition, are part of the (natural) land sink in the definition used in  
516 IPCC Assessment Reports and the Global Carbon Project's annual global carbon budget (Friedlingstein et al., 2022),  
517 while the direct LULUCF fluxes are termed "net land-use change flux", as discussed by Grassi et al. (2018a, 2021,  
518 2022a), Petrescu et al. (2020, 2021b) and Pongratz et al. (2021). Results should thus be interpreted with caution due  
519 to these definitional differences, but as most of the land in Europe is managed and the indirect effects are small, the  
520 definitional differences should be modest compared to other sources of uncertainty (Petrescu et al., 2020). Other  
521 relatively recent studies have already analyzed the European land carbon budget using GHG budgets from fluxes,  
522 inventories and inversions (Luyssaert et al., 2012) and from forest inventories (Pilli et al., 2017; Nabuurs et al., 2018).

523



524 **3.3.2. LULUCF CO<sub>2</sub> fluxes from NGHGI and decadal changes**

525

526 Figure 3 shows the decadal change in CO<sub>2</sub> LULUCF flux from the UNFCCC NGHGI (2019) (upper plot)  
527 compared with the UNFCCC NGHGI (2021) (bottom plot). The contribution of each category (“remaining” and  
528 “conversion”) to the overall reduction of CO<sub>2</sub> emissions in percentages between the three mean periods (gray columns)  
529 are the mean values over 1990–1999, 2000–2009 and 2010–(2017) 2019. The “+” and the “–” signs represent a source  
530 and a sink to the atmosphere. LUC(–) represents the land use conversion changes that increase the strength of the  
531 LULUCF sink between two averages (i.e., values become more negative); LUC(+) represents the land use conversion  
532 changes that decrease the strength of the overall LULUCF sink. Note that the categories inside LUC(–) may be sources  
533 or may be sinks, but between the two average periods, they become more negative. The HWP pool can constitute  
534 either a source or a sink depending on the balance between the timber input to the pool (contributes to a sink) and the  
535 loss of carbon as products reach their end-of-life (source). The absolute contributions of each category to the total  
536 LULUCF fluxes for 1990–2019 are given in Fig. B2 for context.

537 From the 1990–1999 mean to the 2000–2009 mean, the CO<sub>2</sub> LULUCF flux changed from **-87.98 to -96.98** Tg C  
538 in the 2021 NGHGI (i.e., strengthened by 10.0 %), compared with -10.7 % for the 2019 NGHGI (note that Petrescu et  
539 al. (2021b) reported -9.6 %, which is the change relative to the 2000–2009 mean instead of the 1990–1999 mean that  
540 we adopt here due to common usage). This indicates a slight decrease in the reported European land sink compared  
541 to the previous estimates due to revised historical estimates. A 3.8 % growth in emissions from FL-FL and LUC(+)  
542 (Wetlands, Settlements and Other land conversions) weakened the overall sink<sup>10</sup>, while the sink related to all other  
543 categories grew by 15 % to strengthen the overall sink<sup>11</sup>.

544 From the 2000–2009 mean to the 2010–2019 mean, the CO<sub>2</sub> LULUCF flux changed by +3.7 % (i.e., weakened  
545 sink), compared with +3.4 % reported by Petrescu et al., (2021b) which denotes a slight weakening of the European  
546 land sink compared to the previous estimate. Note the difference in time period (2010–2019 here, but 2010–2017  
547 previously). A 9.6 % growth in emissions from FL-FL, HWP and LUC(+) (Forest land, Wetlands, and Settlements  
548 conversions) weakened the overall sink<sup>12</sup>, while the sink related to all other categories changed by -5.9 % and  
549 strengthened the overall sink<sup>13</sup>.

550

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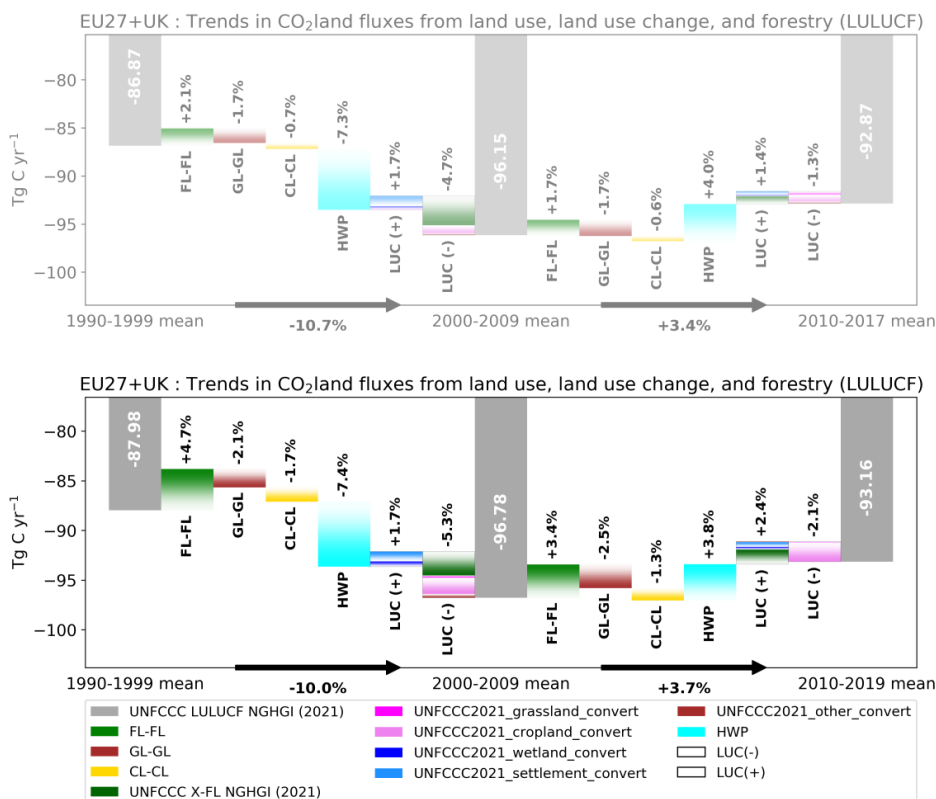
<sup>10</sup> Positive percentages represent sources

<sup>11</sup> Negative percentages represent sinks.

<sup>12</sup> Positive percentages represent sources

<sup>13</sup> Negative percentages represent sinks.





551



552 **Figure 3:** The contribution of changes (%) in CO<sub>2</sub> land fluxes from various LULUCF categories to the overall change  
 553 in decadal mean for the EU27+UK as reported by Member States to the UNFCCC. The top plot shows the previous  
 554 NGHGI data from Petrescu et al. (2021b) and the bottom plot illustrates data from UNFCCC NGHGI (2021). Changes  
 555 in land categories converted to other land are grouped to show net gains and net losses in the same column, with the  
 556 bar color dictating which category each emission belongs to; note that the composition of the “LUC(+)” and  
 557 “LUC(-)” bars can change between time periods. Not shown are emissions from “Wetlands remaining wetlands”,  
 558 “Settlements remaining settlements”, and “Other land remaining other land” as none of the BU models used  
 559 distinguish these categories. The fluxes follow the atmospheric convention, where negative values represent a sink  
 560 while positive values represent a source. The color bars are shaded to guide the eye in the direction of the change  
 561 (white-to-color).

562

563 Similar to Petrescu et al. (2021b), changes of HWP emissions remain by far the major contributor to changes in  
 564 the LULUCF sink strength, but the direction of their contribution is opposite across the two periods: from  
 565 strengthening the sink during 1990–1999 to 2000–2009 to reducing the sink in 2010–2019. However, the balance





566 between HWP and FL-FL is quite sensitive to the periods selected: for the difference between 1993-2001 and 2002-  
567 2010, FL-FL contributes more (+7.3 %) than HWP (-5.2 %). EU-27+UK Member States have all implemented the  
568 IPCC Approach B (i.e., production approach) for the HWP pool (EU NIR, 2021), which “inventories carbon in wood  
569 products from domestically harvested wood only and does not provide a complete inventory of wood carbon in  
570 national stocks” (Volume 4, Chapter 12, IPCC, 2006). Figure 3 suggests that carbon emissions from HWP “end-of-  
571 life” became greater than the amount of carbon entering HWP from domestic harvest in recent decades. If the flux of  
572 carbon into the HWP (a portion of domestic harvest) decreases, there will be a lag effect where outputs (due to wood  
573 product end-of-life) may dominate, leading to a source from HWP. This is confirmed by a more detailed analysis of  
574 the reported gains and losses for the bloc (see Figure A2 in the Appendix), which shows a drop in harvested wood  
575 product gains around 2008 followed by a slower recovery compared to the pre-2008 trend. Gross losses from the  
576 HWP pool, on the other hand, have been increasing as HWP produced pre-2008 reach their end-of-life, leading to a  
577 weakened sink from 2009 onwards compared to during the mid-2000s.

578

### 579 *3.3.3. Estimates of CO<sub>2</sub> land fluxes from bottom-up approaches*

580 In this section we present annual total net CO<sub>2</sub> land emissions between 1990-2020 i.e., induced by both  
581 LULUCF and natural processes (e.g. environmental changes) from class-specific models as well as from models that  
582 simulate multiple land cover/land use classes. The definitions of the classes may differ from the IPCC definitions of  
583 LULUCF (e.g., FL, CL, GL) where, according to IPCC 2006 guidelines, to become accountable in the NGHGI under  
584 “remaining” categories, a land-use type must be in that class for at least N years (where N is the length of the transition  
585 period; 20 years by default). In an effort to create the most accurate comparison as possible in terms of categories and  
586 processes included, total Forest land (FL) has been divided up into Forest land remaining forest land (FL-FL) and  
587 Land converted to forest land (X-FL), while only total Grassland (GL) and Cropland (CL) are reported. This is largely  
588 due to the non-forest sector models explored here only considering net land use change, which prevents separating out  
589 the “converted” component.

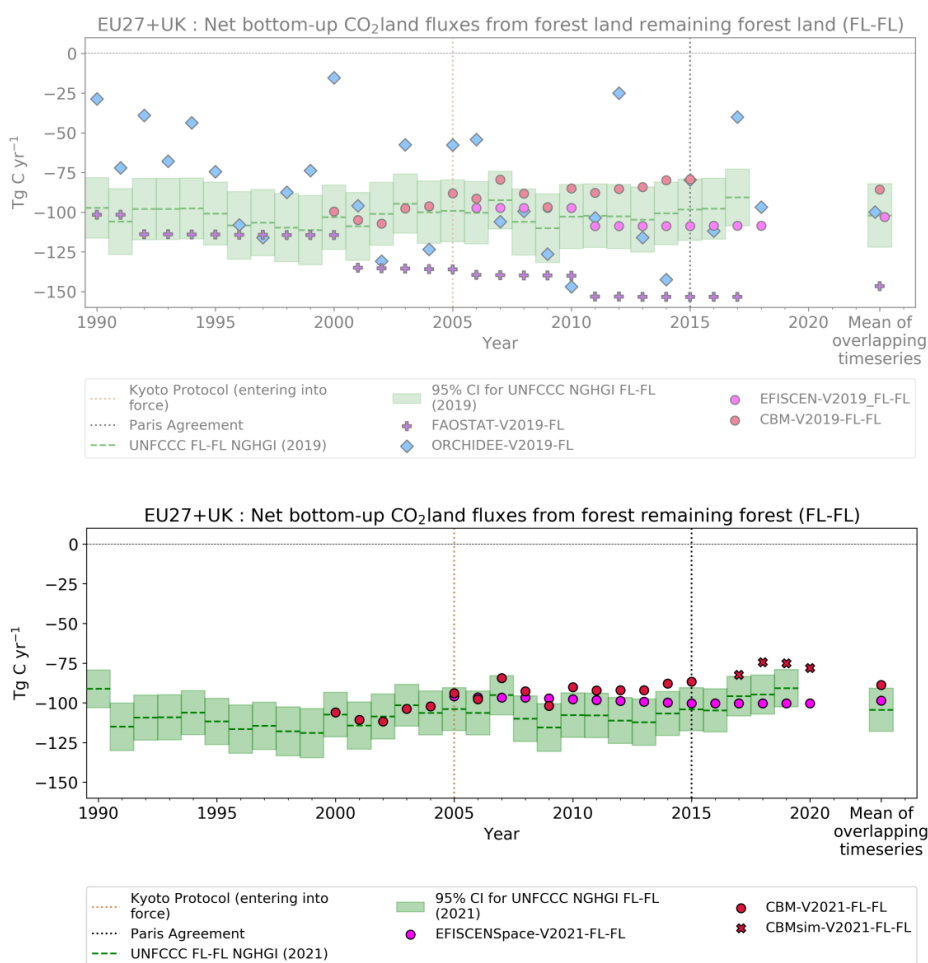
590

#### 591 *Forest land*

592 Fluxes from **Forest land** which remain in this class (FL-FL) are shown in Fig. 4. These fluxes were simulated  
593 with ecosystem models (CBM and EFISCEN-Space, described in more detail in the Appendices) and countries’  
594 official inventory statistics reported to UNFCCC. The results show that the differences between models are systematic,  
595 with CBM having slightly weaker sinks than EFISCEN-Space. CBM updated its historical data (1990-2015) and  
596 presents new NBP estimates based on extrapolation of historical timeseries (see Appendix A2) for 2017-2020  
597 (CBMsim). Both CBM and EFISCEN-Space use national forest inventory (NFI) data as the main source of input to  
598 describe the current structure and composition of European forests. NFIs are also the main source of input data for  
599 most countries in the EU27 for NGHGIs (EU NIR, 2021), including data for carbon stock changes in various pools as  
600 well as the estimation of forest areas. Given that EFISCEN-Space does not cover all countries in the EU27+UK  
601 (Austria, Bulgaria, Denmark, Hungary, Lithuania, Portugal and Slovenia are missing), the results were scaled by  
602 1/0.74 to account for the fact that the available countries comprise around 74 % of the forest NBP for the EU27+UK,



603 according to previous EFISCEN results (Petrescu et al., 2021b). As noted above, EU regulations are driving Member  
 604 States to report spatially explicit NGHGIs. Unlike the original EFISCEN, EFISCEN-Space is a spatially explicit  
 605 model, in addition to being able to simulate a wider variety of stand structures, species mixtures and management  
 606 options. Note that EFISCEN-Space reports only a single mean value for forest fluxes from 2005-2020; the annually  
 607 varying value shown in Fig. 4 arises from scaling by annually varying forest areas.  
 608



609 VERIFY Project  
 610 **Figure 4:** Net CO<sub>2</sub> land flux from Forest land remaining forest land (FL-FL) estimates for EU27+UK CO<sub>2</sub> from the  
 611 Petrescu et al. (2021b) synthesis paper (top) and a comparable graph using the updated data this year (bottom).  
 612 Means are given for 2006-2015 (top) and 2005-2019 (bottom) on the right side of both plots. CBM FL-FL historical  
 613 estimates include 25 EU and UK countries (excl. Cyprus and Malta) and include new estimates for 2017-2020 (red



614 *crosses). The relative error on the UNFCCC value represents the UNFCCC NGHGI (2021) MS-reported uncertainty*  
615 *with no gap-filling (EU NIR, 2021). The fluxes follow the atmospheric convention, where negative values represent a*  
616 *sink while positive values represent a source. Notice that some timeseries have been removed and placed in Fig. 5 as*  
617 *some datasets more accurately depict fluxes from total Forest land (FL).*

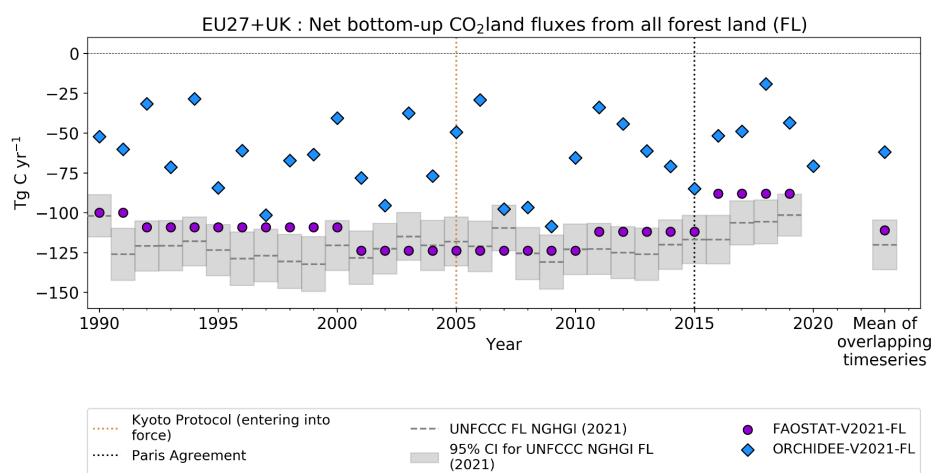
618 The UNFCCC NGHGI uncertainty of CO<sub>2</sub> estimates for FL-FL across the EU27+UK, computed with the  
619 error propagation method (95 % confidence interval) (IPCC, 2006), **ranges between 34 % - 55 %** when analyzed at  
620 the country level for all years, as it varies as a function of the component fluxes (EU NIR, 2019). Despite contrasting  
621 methodologies and input data for emission calculation and uncertainties in each method (Appendix A), there is  
622 reasonable agreement on the trend in FL-FL fluxes from CBMsim and the UNFCCC NGHGI (2021) (Fig. 4). The  
623 magnitude of the values between EFISCEN-Space and the NGHGI (2021) also agree well, though as noted above the  
624 EFISCEN-Space results only vary with the amount of forest area which makes the trend much flatter. Given that all  
625 three methods (NGHGI, CBM, and EFISCEN-Space) are heavily based on national forest inventory data, the general  
626 agreement between the three is not surprising.

627 Figure 5 presents CO<sub>2</sub> land estimates for total Forest land (both remain and convert classes, “FL”). For the  
628 total Forest land, the results were simulated with an ecosystem model (ORCHIDEE) and a global dataset (**FAOSTAT**)  
629 as it is not possible for these two approaches to separate out the “remain” and “convert” land use category. This  
630 obstacle arises due to the use of net land use/land cover information which does not include detailed information on  
631 the nature of the conversions. Consequently, Fig. 5 compares them to the total Forest land from the countries’ official  
632 inventory statistics (UNFCCC NGHGI, 2021).

633 From 2001 and until 2010, the FAOSTAT reports an increasing sink over time, which weakens from 2011  
634 until 2019 (Fig. 5). This is explained by a reporting inconsistency in the Romanian inventory which had not been  
635 corrected at the time of this analysis. Therefore, Romanian estimates for Forestland and Net forest conversion have  
636 been removed for the whole 1990-2020 timeseries in Fig. 5. Starting in 2016, FAOSTAT estimates better match those  
637 from the NGHGIs as FAOSTAT updated its estimates. FAOSTAT uses input data directly from country submissions  
638 to the FAO Global Forest Resource Assessments (FRA<sup>14</sup>) (e.g., carbon stock change is calculated by FAO directly  
639 from carbon stocks and area data submitted by countries). It is important to note that these data are not always identical  
640 to those submitted to the UNFCCC (Tubiello et al., 2021).

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<sup>14</sup>The Global Forest Resource Assessment (FRA) is the supplementary source of Forest land data disseminated in FAOSTAT,  
<http://www.FAO.org/forestry/fra/en/>



641



642 **Figure 5:** Net CO<sub>2</sub> land flux from total Forest land estimates (FL) for EU27+UK CO<sub>2</sub> from the UNFCCC NGHGI  
643 (2021) submissions, the FAOSTAT data-driven inventory, and the ORCHIDEE DGVM. The relative error on the  
644 UNFCCC value represents the UNFCCC NGHGI (2021) MS-reported uncertainty with no gap-filling (EU NIR, 2021).  
645 FAOSTAT data does not include Romanian inventory estimates. The means are calculated for the 1990–2019  
646 overlapping period. The fluxes follow the atmospheric convention, where negative values represent a sink while  
647 positive values represent a source.

648 ORCHIDEE was updated to include a dynamic nitrogen cycle coupled to the carbon cycle in this work. As  
649 shown in Appendix A2, the coupled nitrogen cycle results in a stronger sink, even if identical forcing is used.  
650 ORCHIDEE shows a high inter-annual variability in carbon fluxes for forests in Fig. 5 because it incorporates  
651 meteorological data at sub-monthly timescales, while methods based on forest inventories are generally updated only  
652 every few years (e.g, five years for FRA), which results in a more climatological perspective. ORCHIDEE results  
653 indicate that climatic perturbations and extreme events (multi-month droughts, in particular) can have significant  
654 impacts on the net carbon fluxes depending on their timing in relation to the growing season. This is in line with flux  
655 tower measurements that show significant year to year variability (Ciais et al. 2005). This is also to some extent  
656 supported by dendrometer data although such data varies greatly among sites and tree species which obscures a  
657 significant net effect (Scharnweber et al., 2020). It should also be noted that dendrometer data measures carbon stored  
658 in individual trees, while the NBP reported in figures in this paper include fluxes from litter and soil respiration. The  
659 variability of the weather data affects the carbon dynamics of all components of the ecosystems (hence NBP), which,  
660 for instance, impacts on C assimilation rates, length of the growing season, dynamics of respiration rates and allocation  
661 of the carbon in the plant (cf. Fig. 1 and 2 in Reichstein et al. (2013) and Bastos et al. (2020b)).

662 A few reasons for differences between estimates seen in Fig. 4 and 5 can be readily identified. For this study,  
663 the ORCHIDEE model used the ESA-CCI LUH2v2 PFT distribution (a combination of the ESA-CCI land cover map



664 for 2015 with the historical land cover reconstruction from LUH2 (Lurton et al., 2020)), and assumes that the shrub  
665 land cover classes are equivalent to forest. In terms of area, the original ESA-CCI product corresponding to the  
666 EU27+UK shows shrub land equal to about 50 % of the tree area in 2015. A similar analysis using the FAOSTAT  
667 domain Land Cover, which maps and disseminates the areas of MODIS and ESA-CCI land cover classes to the SEEA  
668 land cover categories<sup>15</sup>, shows that shrub-covered areas are around 20 % of that of forested areas for the  
669 EU27+UK. The impact of classifying shrubs as "forests" on the total carbon fluxes could therefore account for a  
670 significant percentage of the differences between ORCHIDEE and other results in Fig. 5. In addition, CBM depends  
671 strongly on input data and related uncertainty. Historical data are retrieved from both country and EU statistics and  
672 usually refers to forest management units rather than individual inventory plots. Finally, trends in forest carbon  
673 strongly result from management, which are not represented in this version of ORCHIDEE but are included in CBM  
674 and EFISCEN-Space.

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676

#### 677 **Cropland**

678 Cropland (CL, represented in the UNFCCC NGHGI 2021 as UNFCCC category 4B) includes net CO<sub>2</sub>  
679 emissions and **removals from** soil organic carbon (SOC) under “remaining” and “conversion” categories. Figure 6  
680 shows the annual fluxes belonging to the category CL from the NGHGI for the EU27+UK along with four other  
681 approaches: one bottom-up inventory (FAOSTAT), two sector-specific models (EPIC-IIASA, ECOSSE), and one  
682 DGVM (ORCHIDEE). Note that the FAOSTAT value only includes the carbon flux from organic soils drained for  
683 agriculture, while ECOSSE, EPIC-IIASA, and ORCHIDEE include biomass volatilized immediately upon harvest;  
684 biomass left on site to decay as litter; **and soil organic carbon**.

685 **The previous synthesis of Petrescu et al. (2021b) (Fig. 6, top) compared models against results for GL-GL**  
686 **from the NGHGI. For the current work, we compare against the total Grassland values (GL).** The reason for this is  
687 that FAOSTAT, ECOSSE, EPIC-IIASA, and ORCHIDEE all use land use/land cover maps generated by IPCC  
688 Approach 1, which only records the total amount of land in a category for each year; information on transitions  
689 between categories is unknown. Therefore, it is not possible to separate out “remain” and “convert” categories.

690 For the common period (1990-2019), ORCHIDEE simulates a mean sink of -26 Tg C yr<sup>-1</sup>, while ECOSSE,  
691 EPIC-IIASA, and FAOSTAT all simulate mean sources of 21 Tg C yr<sup>-1</sup>, 10 Tg C yr<sup>-1</sup> and 16 Tg C yr<sup>-1</sup>, respectively.  
692 With the exception of ORCHIDEE, all models are in line with the NGHGI results (mean over the same period of 22  
693 Tg C yr<sup>-1</sup>). In Petrescu et al. (2021b) (Fig. 6, top) the NGHGI reported a very small but constant source over the whole  
694 period (mean of 5.6 ± 3.5 Tg C yr<sup>-1</sup>) with almost no inter-annual variability by construction, while all three process-  
695 based models simulated a sink.

696 The sink in ORCHIDEE **must arise from the soil**, as no simulated biomass in croplands remains from year to  
697 year; carbon is assimilated into biomass growth during the growing season, after which the biomass dies, is partitioned  
698 between litter and harvest (50 % to each), and either decays or **vaporizes**, respectively. In other words, no woody or  
699 perennial crops are simulated. **NGHGIs assume that all aboveground biomass of non-woody crops re-enters** the

<sup>15</sup> <http://www.fao.org/faostat/en/#data/LC>



700 atmosphere at harvest. Given more favorable growing conditions due to climatic changes and CO<sub>2</sub> fertilization, this  
701 leads to more carbon entering the soil in ORCHIDEE in recent decades, which is driving the calculated CL sink  
702 observed in the model.

703 In the NGHGI, the reported source for the EU27+UK is mostly attributed to emissions from cropland on  
704 organic soils<sup>16</sup> in the northern part of Europe where CO<sub>2</sub> is emitted due to C oxidation from tillage activities and  
705 drainage of peat. The fact that FAOSTAT values are similar to the UNFCCC values points to the primary role of  
706 drained organic soils, as this is the only flux included for the FAOSTAT dataset in Fig. 6. Finland and Sweden are of  
707 particular importance, as they together account for more than half of the total area of organic soil in Europe. Organic  
708 soils are an important source of emissions when they are under management practices that disturb the organic matter  
709 stored in the soil. In general, the NGHGI emissions from these soils are reported using country-specific values when  
710 they represent an important source within the total budget of GHG emissions.

711 ORCHIDEE also shows a much larger year-to-year variation due to the response of vegetation and respiration  
712 fluxes to sub-daily meteorology. EPIC-IIASA and ECOSSE both operate on daily timescales (ECOSSE was updated  
713 to daily for this work, though the previous version was monthly). As both photosynthesis (e.g., Kumarathunge et al.,  
714 2019) and respiration (e.g., Yvon-Durocher et al., 2012) show non-linear dependence on temperature, the more  
715 extreme temperatures experienced by plants in ORCHIDEE will lead to a higher variation in vegetation response given  
716 the same photosynthetic model. High IAV can be seen clearly for drought impacts in ORCHIDEE where regions  
717 change from sources to sink in a single year (e.g., for 2003 and 2018 (Ciais et al., 2005; Bastos et al., 2020a)). The  
718 other two ecosystem models follow ORCHIDEE's patterns but with smaller magnitudes. FAOSTAT and NGHGIs  
719 are mostly insensitive to inter-annual variability as the estimations are mainly based on statistical data for  
720 surfaces/activities and emission factors that do not vary with changing environmental conditions.

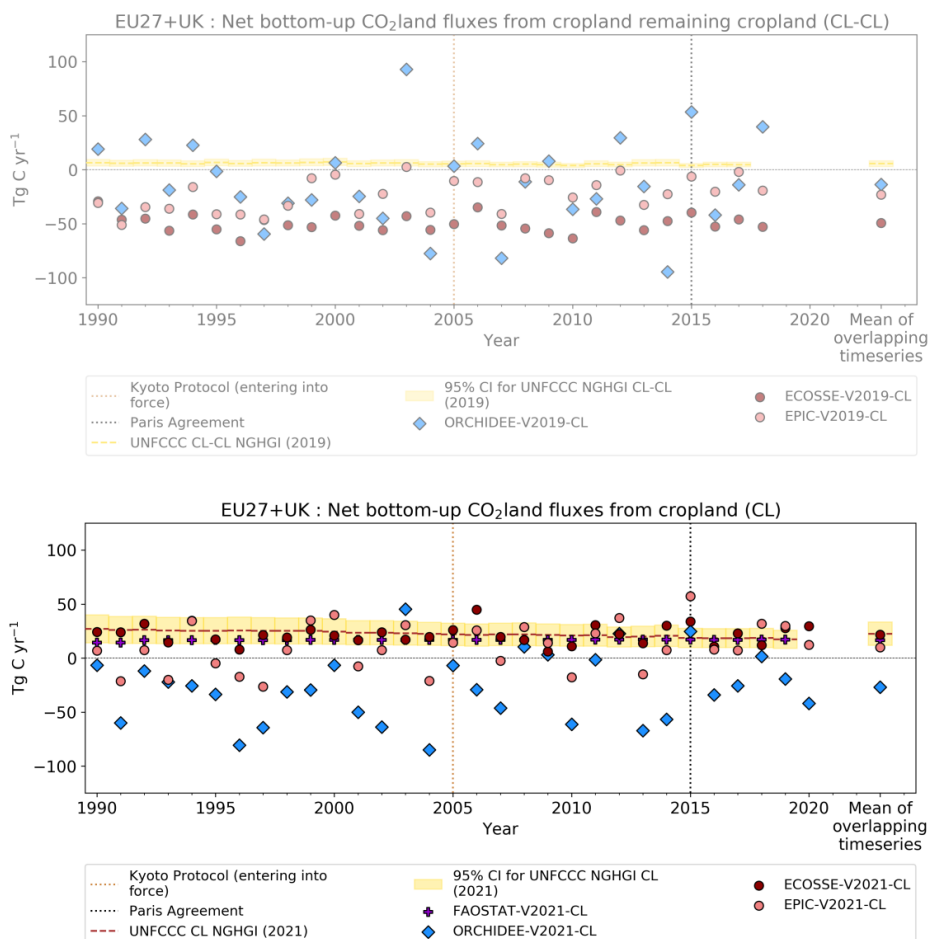
721 Both ECOSSE and EPIC show a striking improvement in agreement with the NGHGI between V2019 (Fig.  
722 6, top) and the current work (Fig. 6, bottom). For ECOSSE, this is the result of improved data, in particular around  
723 residue management. The aboveground biomass is divided into harvest (which is accounted as direct emissions) and  
724 residues (biomass that is partly removed and partly left on the field). The external tool MIAMI serves as the central  
725 model for the NPP and follows the allocation distribution of Neumann and Smith (2018). The removed residues are  
726 set to 50 % as a compromise between the wide range of residue removal rates given by Scarlat et al. (2010). Residue  
727 and yield biomass from MIAMI are provided as input into the ECOSSE simulations. Additionally, more realistic  
728 fertilizer data (Mueller et al., 2012) were used. For EPIC, the shifts in net CO<sub>2</sub> fluxes in the current EPIC results stem  
729 from the updated soil organic carbon and nitrogen module (Balkovič et al., 2020) and updates in meteorological  
730 forcing. Firstly, the updated soil module resulted in higher heterotrophic respiration across many EU regions. Besides  
731 attributing more carbon to the soil surface emissions, enhanced respiration leads to higher NPP and yields in regions  
732 with low fertilization rates as more nitrogen is released from the SOM pool. Secondly, altered solar radiation and air

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<sup>16</sup>The 2006 IPCC Guidelines largely follow the definition of Histosols by the Food and Agriculture Organization (FAO), but have omitted the thickness criterion from the FAO definition to allow for often historically determined, country-specific definitions of organic soils (see Annex 3A.5, Chapter 3, Volume 4 of IPCC (2006) and Chapter 1, Section 1.2 (Note 3) of IPCC (2014)).



733 temperature data affected the full range of carbon variables in EPIC, including NPP, harvested biomass, heterotrophic  
 734 respiration, and leached carbon.  
 735



736 VERIFY Project  
 737 **Figure 6:** Net CO<sub>2</sub> land flux from Cropland estimates for the EU27+UK from: previous data from Petrescu et al.,  
 738 (2021b) showing only the “remaining” fluxes (CL-CL) (top plot), and data from the UNFCCC NGHGI (2021)  
 739 submissions and models showing net carbon fluxes for the total Cropland (CL), with their 1990-2019 mean given on  
 740 the right (bottom plot). CL net carbon fluxes are estimated with three ecosystem models: ORCHIDEE, ECOSSE and  
 741 EPIC-IIASA, in addition to the FAOSTAT inventory. Note that the FAOSTAT value only includes the carbon flux from  
 742 organic soils drained for agriculture. The relative error on the UNFCCC value represents the UNFCCC NGHGI  
 743 (2021) MS-reported uncertainty with no gap-filling (EU NIR, 2021). The fluxes follow the atmospheric convention,  
 744 where negative values represent a sink while positive values represent a source.





745

746 Finally, differences in the results between the models and the NGHGs may arise from definitions. The  
747 cropland definition in the IPCC includes cropping systems and agroforestry systems where vegetation falls below the  
748 threshold used for the definition of Forest land category, consistent with the selection of national definitions (IPCC  
749 glossary). Given that every country is allowed to select their definition of Forest land, which therefore influences the  
750 area of Cropland and the total emissions, it is beyond the scope of this study to summarize here the criteria for the 28  
751 countries under consideration and compare those to the methods used in determining the land use/land cover data for  
752 the other models. However, the interested reader is referred to Tables 6.10 (forests), 6.18 (croplands), and 6.22  
753 (grassland) in the 2022 NIR of the European Union (EEA/PUBL/2022/023).

754

#### 755 *Grassland*

756 Grassland (GL, UNFCCC category 4C) includes net CO<sub>2</sub> emissions and removals from soil organic carbon  
757 (SOC) under “remaining” and “conversion” categories. The grassland definition in the IPCC includes rangelands and  
758 pasture land that is not considered as Cropland, as well as systems with vegetation that fall below the threshold used  
759 in the Forest land category (same explanation as for Cropland). This category also includes all grassland from wild  
760 lands to recreational areas as well as agricultural and silvo-pastoral systems, subdivided into managed and unmanaged,  
761 consistent with national definitions (Petrescu et al., 2021b). For similar reasons to those expressed in the section  
762 Cropland above, the current work (Fig. 7, bottom) compares modeled CO<sub>2</sub> flux against NGHGI results for total  
763 Grassland (GL).

764 The NGHGs of countries in the EU27+UK report emissions from managed pastures and grasslands, although  
765 the details of what is included varies between countries (Table 6.21, EU NIR, 2021). Grasslands can be managed  
766 through grazing or by cutting. If a grassland is used for grazing but retains the natural vegetation, it is called a  
767 “rangeland”. If the area has been replanted with vegetation specifically for animal forage, it is commonly referred to  
768 as “pasture”<sup>17</sup>. Since almost all European grasslands are somehow modified by human activity and to a major extent  
769 have been created and maintained by agricultural activities, they can be defined as “semi-natural grasslands”, even if  
770 their plant communities are natural (Silva et al., 2008).

771 The NGHGI reports a slightly positive net flux over 1990-2019, although with a much larger uncertainty than  
772 for either Forest land or Cropland ( $4 \pm 28$  Tg C yr<sup>-1</sup>). While increased uncertainty compared to forest emissions is  
773 understandable given the emphasis on collecting accurate forestry statistics due to their economic importance, the  
774 increased uncertainty in Grassland compared to Cropland is more puzzling. Three possible explanations include: 1)  
775 absolute Grassland emissions/removals are lower than for Cropland, which may lead to higher relative uncertainty  
776 given the nearness to zero; 2) MS with lower uncertainties may dominate Cropland, while MS with higher  
777 uncertainties may dominate Grassland; 3) Extensive work has been carried out on national/regional factors  
778 representing changes in Cropland management, while less has been done on Grassland. For (3), this also may apply  
779 to other biomass pools, as eight countries report “country specific” instead of “default” parameters for living biomass

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<sup>17</sup> See, for example, <https://www.epa.gov/agriculture/agricultural-pasture-rangeland-and-grazing>



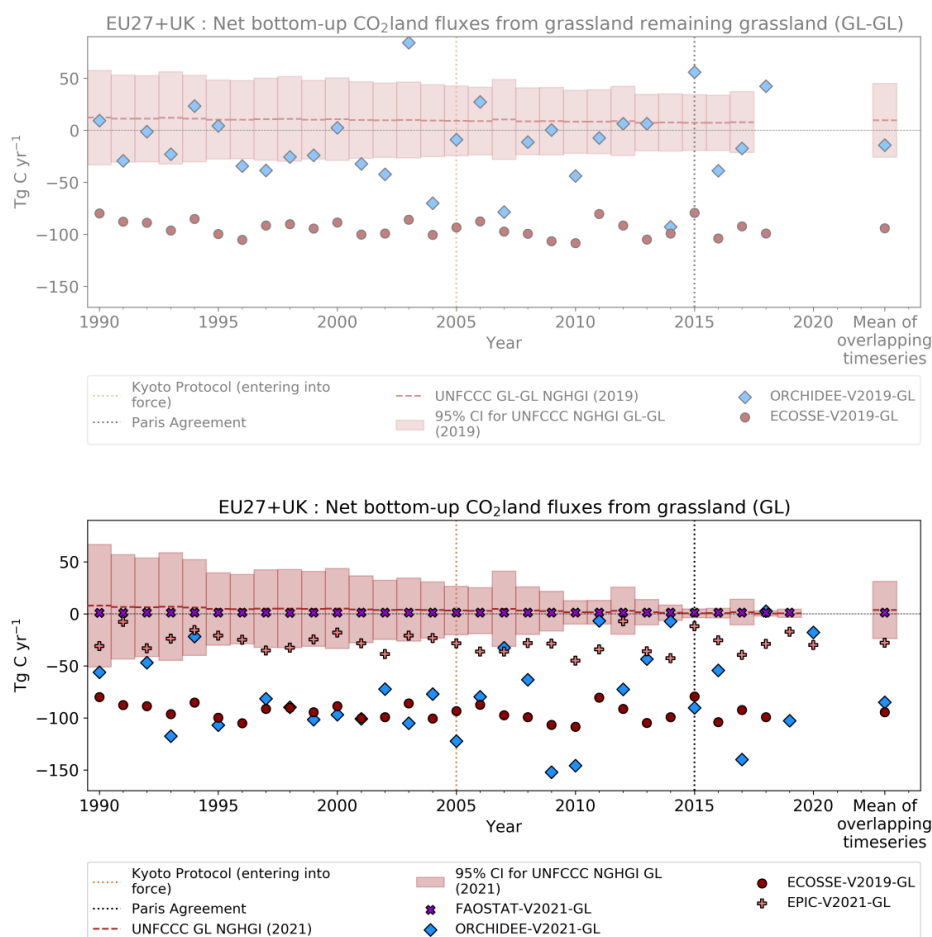


780 in Cropland versus Grassland (while only one country does the reverse; Table 6.6., EU NIR, 2021). Additional  
 781 analysis will be needed to elucidate this issue.

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786 **Figure 7:** Net CO<sub>2</sub> land flux from total Grassland (GL) estimates for EU27+UK from: previous data from Petrescu *et*  
 787 *al.* (2021b) (top plot), and the updated datasets considered here (bottom plot). The means shown on the right of each  
 788 plot are for 1990–2017 (top) and 1990–2018 (bottom). GL net carbon fluxes are estimated with the ORCHIDEE, EPIC-  
 789 IIASA, and ECOSSE (not updated and therefore identical to Petrescu *et al.*, 2021b) models in addition to FAOSTAT.  
 790 The relative error on the UNFCCC value represents the UNFCCC NGHGI (2021) MS-reported uncertainty with no  
 791 gap-filling (EU NIR, 2021). The fluxes follow the atmospheric convention, where negative values represent a sink  
 792 while positive values represent a source.



793

794 In addition to the NGHGI, updated results are available for ORCHIDEE (using a coupled C-N cycle) and  
795 FAOSTAT. For the first time, EPIC-IIASA contributed estimates for Grassland fluxes using five different grassland  
796 types and simulating carbon export due to herbivores (see Appendix A2 for more details). Both of these models  
797 exhibit a strong sink in Grassland. For ORCHIDEE, this is likely due to the same reasons as the sink in croplands:  
798 more suitable growing conditions due to climate change, CO<sub>2</sub> fertilization, and nitrogen deposition leading to increased  
799 inputs into the soil which are not lost during tillage due to the lack of explicit management in the version reported  
800 here. For EPIC-IIASA, this results from manure left on site and incorporated into the soil. A Tier 1 IPCC approach  
801 assumes no changes in either living or dead biomass pools on grasslands; **only considers** organic soils which have  
802 been drained for grazing; and **only** considers mineral soils which have undergone a change in management. This  
803 greatly reduces or eliminates mechanisms which promote sinks in ORCHIDEE and EPIC-IIASA. On the other hand,  
804 FAOSTAT reports a slight source in Grasslands, in line with the NGHGI. This is because, as is the case for Cropland,  
805 FAOSTAT data only considers emissions from drained organic soils. As incorporation of manure in EPIC-IIASA  
806 changes grasslands from a net source to a net sink, consideration of CO<sub>2</sub> from manure input in other inventories may  
807 have a similar effect.

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#### 809 **3.3.4. Bottom-up CO<sub>2</sub> estimates from all LULUCF categories**

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811 This section analyzes CO<sub>2</sub> emissions and sinks for the LULUCF sector, including NGHGI categories (from  
812 Fig. 3) and a suite of different bottom-up approaches. This comparison is challenging due to differences in terms of  
813 activities covered in the different estimates, as well as differences in terminology (see, for example, Petrescu et al.,  
814 2020, Fig. 12). To summarize:

- 815 • FAOSTAT differs from NGHGIs for reasons recently summarized by Tubiello et al. (2021), Petrescu et al.  
816 (2021b), and Grassi et al. (2022a), including numerically different data provided by Member States to  
817 FAOSTAT and UNFCCC; different methods (FAOSTAT applies a Tier 1 approach globally, while Member  
818 **States** reports to the UNFCCC vary from Tier 1 to Tier 3); differences between net and gross land use change  
819 (FAOSTAT is based on net transitions, following Approach 1 as detailed by the 2006 IPCC guidelines  
820 (Chapter 3 of Volume 4, Sect. 3.3.1)); and differences in biomass pools. For the latter, FAOSTAT only  
821 considers living biomass pools instead of the five IPCC pools<sup>18</sup> reported to the UNFCCC. A preliminary  
822 examination shows that changes in dead wood, litter, and mineral soil carbon stock are generally less than  
823 0.1 t C/ha, which is relatively small compared to reported changes around 1.0 t C/ha in living biomass pools  
824 (Tables 6.13, 6.14, 6.15, EU NIR, 2021). On the other hand, changes in organic soil carbon stock are  
825 approximately the same magnitude as living biomass, which may lead to significant discrepancies between  
826 the NGHGI and FAOSTAT for the EU27.

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<sup>18</sup> According to the IPCC 2006 guidelines the reporting is done for the five LULUCF carbon pools: above-ground biomass, belowground biomass, dead wood, litter, and soil organic matter



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- DGVMs (represented here by the TRENDY v10 ensemble, as well as the high-resolution ORCHIDEE and CABLE-POP simulations) include the impact of CO<sub>2</sub> fertilization, climate change and land use change for Forest land, Grassland and Cropland categories; they do not explicitly treat the Wetlands, Settlement and Other land categories as in the NGHGs. They account for the evolution of living biomass, dead biomass, and soil organic carbon for all categories while for NGHGs reporting is not mandatory for all subcategories depending on the method Tier employed (e.g., dead organic matter in a Tier 1 method is assumed to be constant). There is significant uncertainty associated with the DGVMs' fluxes both from i) the forcing data, including datasets of land-use changes and the coverage of different land use change practices, ii) model parameters, and iii) model structural uncertainty (i.e., processes not included) (Arneth et al., 2017). Similar to FAOSTAT, DGVMs typically deal with net land use change emissions at the spatial resolution of the model simulations (e.g., 0.5° or 1° for the TRENDY ensemble and 0.125° for the ORCHIDEE and CABLE-POP simulations) instead of gross land use change as reported in NGHGs. CABLE-POP is an exception to most DGVMs and actually incorporates gross land use transitions (Haverd et al., 2018). The use of gross land use transitions may induce significant differences with coarse resolution model simulations (e.g., the TRENDY ensemble). In addition, DGVMs often do not distinguish between managed and unmanaged land, while NGHGs report results only from managed land.
  - The bookkeeping models, BLUE and H&N, calculate net emissions from land use change including immediate emissions following land conversion, legacy emissions from slash and soil carbon decomposition after land-use change, carbon uptake during regrowth of secondary forest after pasture and cropland abandonment, and emissions from harvested wood products as they decay. While activities on the category Land remaining land are generally not considered in bookkeeping models, one major exception is fluxes from wood harvest, which are a primary source of emissions on managed forest land. In addition, bookkeeping models do not account for fluxes arising from “indirect” anthropogenic influences such as CO<sub>2</sub> fertilization or climate change.

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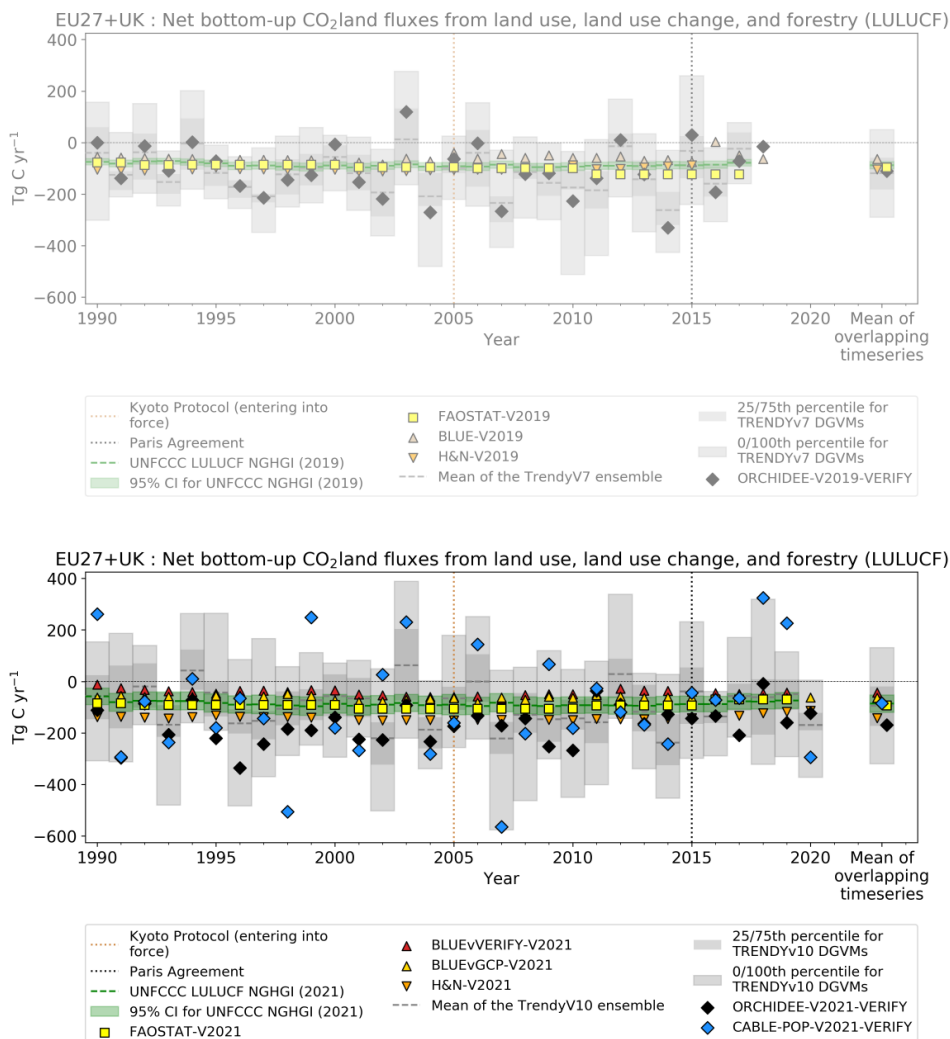
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Given all these differences in terms of activities, the comparison in this section should be considered as a rough overview that highlights both important aspects of the C cycle and questions that need to be addressed in the future. Going towards a more specific comparison of only net land-use change (LUC) fluxes would require additional considerations. In GCP's annual global carbon budget, net LUC term is estimated by global DGVMs as the difference between a run with and a run without land-use change (i.e., the S3 and S2 simulations from TRENDY, respectively) and by bookkeeping models (Friedlingstein et al., 2022). Such an estimate is given in Fig. 13 in Petrescu et al. (2020) for Forest land. However, this approach does not fully resolve the differences mentioned above. In particular, questions remain about net vs. gross land use change, managed vs. unmanaged land, and emissions from wood harvest. In addition, UNFCCC “convert” emissions (i.e., emissions resulting from land that has been converted from one type to another) are reported within 20 years following conversion in the “convert” category (biomass losses are typically reported in the year of conversion, while net changes in soil organic carbon during the entire conversion period). FAOSTAT, DGVMs, and bookkeeping models usually only include “convert” fluxes from the year following



864 conversion, although bookkeeping models and DGVMs which deal with gross transitions may be able to include this  
 865 transition period more easily.



866 VERIFY Project  
 867 *Figure 8: Net CO<sub>2</sub> fluxes from total LULUCF activities in the EU27 + UK from previous data from Petrescu et al.*  
 868 *(2021b) (top plot) and data from seven new or updated sources (bottom plot) including: UNFCCC NGHGI (2021),*  
 869 *BLUE (vVERIFY), BLUE (vGCP2021), H&N (GCP2021), DGVMs (TRENDY v10), FAOSTAT (2021), ORCHIDEE*  
 870 *and CABLE-POP with high-spatial-resolution (0.125°) meteorological forcing (both models are also part of the*  
 871 *TRENDY ensemble at 0.5°). The gray bars represent the individual model data for the DGVMs. The UNFCCC estimate*  
 872 *includes all classes (remain and convert), as well as HWP. The relative error of the UNFCCC values represent the*



873 UNFCCC NGHGI (2021) Member States reported uncertainty computed with the error propagation method (95 %  
874 confidence interval), gap-filled and provided for each year of the timeseries. Biomass burning emissions are included  
875 in the C stock estimates. The FAOSTAT estimate includes both Forest land remaining forest land in addition to  
876 incorporating afforestation and deforestation as conversion of Forest land to other land types. The means are  
877 calculated for the 1990–2019 overlapping period. The fluxes follow the atmospheric convention, where negative  
878 values represent a sink while positive values represent a source.

879 Figure 8 shows CO<sub>2</sub> fluxes from the NGHGI LULUCF sector compared to all other comparable bottom-up  
880 (BU) estimates in this work: high-resolution S3 simulations for both ORCHIDEE and CABLE-POP; the median of  
881 15 S3 simulations from the TRENDYv10 DGVM ensemble; three bookkeeping models; and FAOSTAT. As  
882 mentioned above, taking the difference of the TRENDY S2 and S3 simulations provides an estimate of the net flux  
883 from land use change, but inconsistencies are introduced either way, and therefore further research is needed in order  
884 to establish which approach (S3-S2, or simply S3) leads to the most consistent comparison. For the overlapping period  
885 1990-2019, the means of two out of the three bookkeeping models (BLUE vGCP (-61 Tg C yr<sup>-1</sup>) and BLUE vVERIFY  
886 (-43 Tg C yr<sup>-1</sup>, using the Hilda+ land use forcing)) along with the mean of FAOSTAT (without Romania) (-93 Tg C  
887 yr<sup>-1</sup>) fall within the 95 % confidence interval of the UNFCCC NGHGI estimate of -86 ± 33 Tg C yr<sup>-1</sup>. Only H&N rests  
888 apart with a stronger sink (-142 Tg C yr<sup>-1</sup>).

889 Bookkeeping models like BLUE and H&N do not include indirect effects on biomass growth due to factors  
890 such as CO<sub>2</sub> fertilization, nitrogen deposition, and climate change, while NGHGIs implicitly include these impacts on  
891 managed land through updated statistics. Recent work by Grassi et al. (2022b) demonstrates that including the sink  
892 associated with human-induced indirect effects (as estimated by the S2 simulations from the TRENDY DGVM  
893 ensemble) into results by bookkeeping models can largely reconcile estimates of net global LULUCF fluxes between  
894 the NGHGIs and bookkeeping models. At the level of the EU27+UK, the inclusion of this sink results in an  
895 overcompensation; the BMs estimate a net sink of -56.5 Tg C yr<sup>-1</sup> compared to the NGHGI estimate of -87.9 Tg C yr<sup>-1</sup>,  
896 while the BMs+DGVMs results in -112 Tg C yr<sup>-1</sup>. However, all of these estimates fall inside the NGHGI uncertainty  
897 range in Fig. 8. This suggests that indirect effects are small in the EU27+UK.

898 The UNFCCC LULUCF estimates contain CO<sub>2</sub> emissions from all six land use categories and HWP,  
899 including remaining categories and conversion to and from a category to another. The DGVMs show high interannual  
900 variability, as demonstrated clearly by the high-resolution CABLE-POP simulation in Fig. 8. The mean values for  
901 DGVMs across the overlapping period, on the other hand, agree fairly well with the NGHGI: -170 Tg C yr<sup>-1</sup>, -84 Tg  
902 C yr<sup>-1</sup>, and -81 (min -285, max 118) Tg C yr<sup>-1</sup> for ORCHIDEE, CABLE-POP, and TRENDY v10, respectively,  
903 compared to the NGHGI mean of -86 ± 33 Tg C yr<sup>-1</sup>. Note again that ORCHIDEE and CABLE-POP are also part of  
904 the TRENDYv10 ensemble, but the simulations included in TRENDY used a coarser meteorological forcing than the  
905 one used within the VERIFY project (around 0.125° resolution). CABLE-POP also used a higher resolution land use  
906 land cover change (LULCC) dataset for the results submitted to VERIFY (0.25° as opposed to 1.0°). The increased  
907 IAV from the high-resolution CABLE-POP compared to ORCHIDEE is suspected to have been introduced through  
908 the construction of the LULCC dataset as described in Appendix A2. Gross fluxes are, by definition, larger than net



909 fluxes, and consequently a method which incorporates gross fluxes (like CABLE-POP) can be expected to undergo  
910 larger changes than a method incorporating net fluxes (like ORCHIDEE).

911 The differences between bookkeeping models and UNFCCC and FAOSTAT are discussed in detail  
912 elsewhere, and focus on the inclusion of unmanaged land in bookkeeping models but not FAOSTAT and UNFCCC  
913 methodologies (Petrescu et al., 2020; Grassi et al., 2018a, 2021). ORCHIDEE, CABLE-POP and the TRENDY v10  
914 ensemble means show much higher inter-annual variability due to the sensitivity of the model fluxes to highly variable  
915 meteorological forcing at sub-daily time steps which allow for much more rapid responses to changing conditions, as  
916 already discussed in the previous sections. The incorporation of variable climate data and the fact that DGVM models  
917 simulate explicitly climate impacts on CO<sub>2</sub> fluxes, which inventories and bookkeeping models do not, explain these  
918 differences. A comparison including sector-specific models (e.g., ECOSSE, EFISCEN-Space, EPIC-IIASA, CBM)  
919 where multiple model results are harmonized and aggregated to produce a “total” LULUCF flux comparable to  
920 DGVMs and bookkeeping models would be insightful; however, such a comparison requires extensive analysis which  
921 is beyond the scope of the current work.

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### 923 3.3.5. Comparison of atmospheric inversions with NGHGI CO<sub>2</sub> estimates

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925 Figure 9 highlights the range of estimates from global and regional atmospheric inversions (GCP2021,  
926 EUROCOM, CSR, LUMIA, and CIF-CHIMERE; see Table 2 and Appendix A2 for more details) against bottom-up  
927 total annual EU27+UK CO<sub>2</sub> land emissions/removals from the UNFCCC NGHGI (2021). The top panel in the figure  
928 shows the previous results from Petrescu et al. (2021b). In these inversions, all components of the carbon cycle that  
929 contribute to the observed atmospheric CO<sub>2</sub> gradients between stations are implicitly included as the inversions  
930 incorporate observed atmospheric concentrations of CO<sub>2</sub>. This includes processes where carbon is uptaken by  
931 vegetation in one area and emitted in a different area, i.e. emissions due to the respiration of laterally transported  
932 carbon.

933 One significant change between this work and Petrescu et al. (2021b) is the removal of emissions and sinks  
934 from inversion results due to lateral transport of carbon from crop trade, wood trade, and inland waters. Bottom-up  
935 methods (including all the NGHGIs for European countries) do not consider emissions and removal of atmospheric  
936 CO<sub>2</sub> due to lateral transport of carbon, while observations assimilated into top-down inversions record all CO<sub>2</sub> fluxes  
937 without separating their components. We followed Eq. (1) of Deng et al. (2021) without prior masking for managed  
938 land. Emissions from lateral transport of carbon (“lateral fluxes”) were prepared generally following the approach  
939 described by Ciais et al. (2021), where crop and wood product fluxes are derived from country-level trade statistics  
940 compiled by the FAO. Inland water emissions and riverine export of terrestrial carbon use spatially explicit  
941 climatological data and a statistical model combined with estimates of gas transfer velocities. A more complete  
942 description is given in Appendix A2. This adjustment has been applied to all top-down fluxes reported here unless  
943 indicated otherwise.

944 The C fluxes from inland waters (rivers and lakes) reported in Petrescu et al. (2021b), were replaced in this  
945 study by maps of sinks/sources of rivers/lakes, wood and crops, accounting for a combined mean of -136 Tg C yr<sup>-1</sup>  
946 (over the 2010-2018 common period of the inversions). For comparing bottom-up methods (including the NGHGI) to



947 TD estimates in the EU27+UK, it is always necessary to remove the traded wood and crop harvest (see Deng et al.  
948 (2021) for additional explanations). For the NGHGI, this arises due to how harvested wood products are considered.  
949 HWPs can be reported to the UNFCCC by multiple approaches, three of which are outlined in Chapter 12 of Volume  
950 4 of the 2006 IPCC Guidelines. One of these methods (the Atmospheric Flow Approach) would allow for a direct  
951 comparison with the inversions as wood product emissions are accounted for in countries in which they are in use and  
952 in landfills. However, all countries in the EU27 adopt the Production Approach (2022 NIR of the European Union  
953 (EEA/PUBL/2022/023)) in which emissions are considered due to domestic harvest regardless of where the wood is  
954 transformed or used. Inversions, on the other hand, see the HWPs where they transform into CO<sub>2</sub>, either through  
955 decomposition or **incineration**. It should be noted that DGVMs also typically implement the Production Approach on  
956 a pixel level (i.e., harvested wood decomposes in the pixel where it is produced). As pixels reported for the high-  
957 resolution simulations here are around 10 km wide, this implicitly assumes that HWP never travel more than 10 km  
958 from the harvest site (this becomes 50 km in coarser resolution simulations like TRENDY). **Therefore, removing**  
959 **emissions from lateral carbon transport makes inversions** more comparable not only to NGHGI but also to DGVMs.

960 Flux estimates from inversion methods for CO<sub>2</sub> land show much more variability than the NGHGI (Fig. 9).  
961 The mean of the EUROCOM ensemble of European inversions shows good agreement with UNFCCC NGHGI data,  
962 but with a huge spread of annual model results that extends from significant sources into large sinks. **This large spread**  
963 can be linked to uncertainty in atmospheric transport modeling, inversion methods and assumptions, and to limitations  
964 of the observation system. Furthermore, the EUROCOM inversions were designed for the European geographical  
965 domain (which is larger than the EU27+UK) and are still being developed in particular to better constrain the  
966 latitudinal and longitudinal boundary conditions.

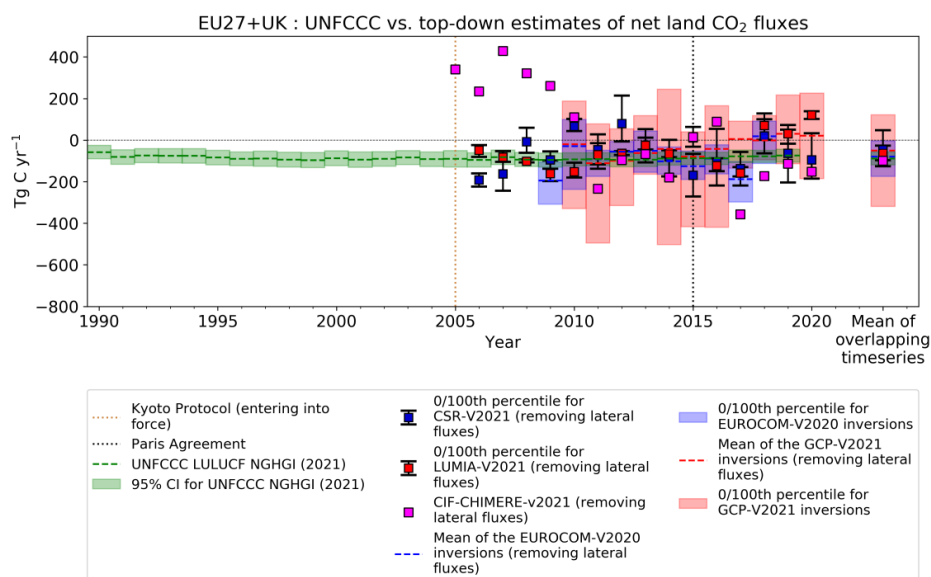
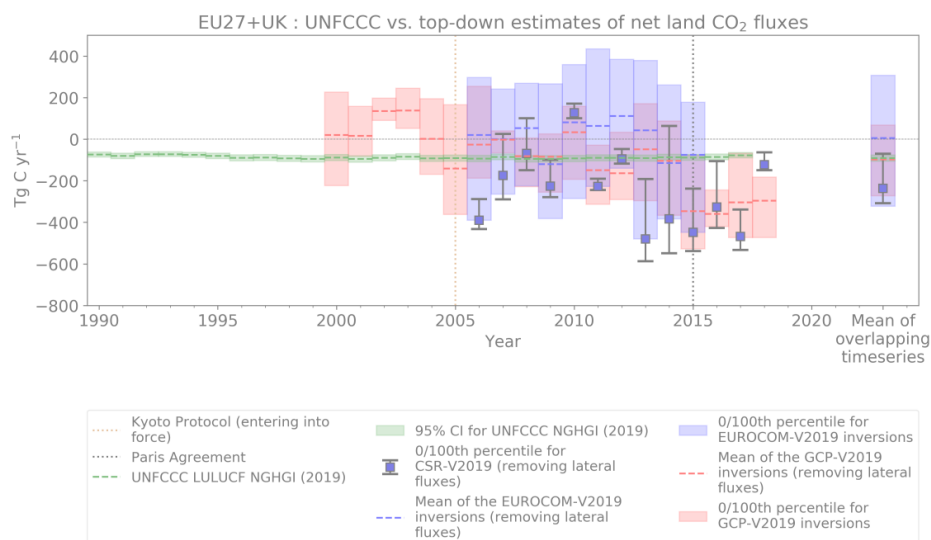
967 **The** annual mean (overlapping period 2010-2018) of the EUROCOM v2021 inversions (-80 [-175,-4] Tg C  
968 yr<sup>-1</sup>) is the closest inversion estimate to the timeseries mean of the NGHGI estimates (-88 ± 31 Tg C yr<sup>-1</sup>), where the  
969 error bars for the inversion indicated the [0th,100th] percentiles due to the small size of the ensembles. The mean of  
970 the global GCP2021 inversions (-50 [-320,+122] Tg C yr<sup>-1</sup>) and regional inversions, CSR (-46 [-126,+47] Tg C yr<sup>-1</sup>)  
971 and LUMIA (-65 [-97,-27] Tg C yr<sup>-1</sup>) show a lower absolute value, but report larger interannual variability (min/max).  
972 The new CIF-CIMERE product has a mean of -99 Tg C yr<sup>-1</sup>, showing more negative fluxes since 2010, which is not  
973 seen in other models and is still under investigation.

974





975



976



977 *Figure 9: Comparison of inventories and atmospheric inversions for the total EU27+UK biogenic CO<sub>2</sub> fluxes from*  
 978 *Petrescu et al. (2021b) (top plot) and updated data from current study (bottom plot). Top-down inversion results are:*  
 979 *the global GCB2021 ensemble, the regional EUROCOM ensemble, the regional CarboScopeReg model with multiple*  
 980 *variants, the regional LUMIA model with multiple variants, and CIF-CHIMERE. The relative error in the UNFCCC*





981 values represents the UNFCCC NGHGI (2021) Member states reported uncertainty computed with the error  
982 propagation method (95 % confidence interval) gap-filled and provided for every year of the timeseries. The timeseries  
983 mean overlapping period is 2010-2018. The colored area represents the min/max of model ensemble estimates. The  
984 same emissions due to lateral fluxes of carbon through rivers, crop trade, and wood trade are removed from the top-  
985 down estimates in both the top and bottom graphs for consistency. The fluxes follow the atmospheric convention,  
986 where negative values represent a sink while positive values represent a source. Note that Petrescu et al. (2021b)  
987 presented the top plot including a suite of bottom-up models, which have been removed here for clarity as they have  
988 already been presented in Fig. 8.

989

990 The comparison of past and current versions of the inversions shows changes in specific models. A reduction  
991 in the spread of the estimates is noted over the two past versions of CSR, resulting in a small source in the most recent  
992 estimates. The CSRv2021 (bottom-plot) predicts in 2018 (last common year of both versions) a small source of 19 [-  
993 64, +100] Tg C yr<sup>-1</sup> compared to the previous CSRv2019 which simulated a very strong sink of -253 [-280, -194] Tg  
994 C yr<sup>-1</sup>. This smaller source appears more in line with more positive fluxes expected in years of extreme drought (e.g.,  
995 2018 in Northern Europe, although this did not impact the whole EU27+UK (Toreti et al., 2019)).

996 As can be seen in Fig. 9, there is also improved agreement between the EUROCOM ensemble and the  
997 NGHGI, including a greatly reduced IAV compared to the previous version. The small EUROCOM ensemble mean  
998 sink for the 2009-2015 period of -1.9 [-335,+322] Tg C yr<sup>-1</sup> (top panel) strengthened to -93 [-187,-15] Tg C yr<sup>-1</sup> in the  
999 v2021 version (bottom panel). The UNFCCC total LULUCF mean is  $-92 \pm 33$  Tg C yr<sup>-1</sup> for the same time period. The  
1000 IAV of EUROCOM was dramatically reduced by removing the FLEXINVERT model from the v2021 ensemble as a  
1001 clear outlier of annual means due to a slightly shifted seasonal cycle (Appendix A2).

1002 The new GCP2021 inversions show a clear trend towards decreasing the CO<sub>2</sub> sink strength of the land surface  
1003 after 2017, contrary to the NGHGI estimates which are relatively stable (Fig. 9, bottom). The large variability and  
1004 high sink observed in the upper plot of Fig. 9 shifted to a source in 2019 (21 [-185, +226] Tg C yr<sup>-1</sup>) due to the extreme  
1005 climatic response of the TD models to the drought year, which can also be observed in the BU simulations (e.g.,  
1006 TRENDY v10, ORCHIDEE, and CABLE-POP in Fig. 8). Out of the GCP2021 models, CAMS was the model  
1007 responsible for the lower sinks (data not shown), which may be due partly to changes in the stations assimilated.

1008 Table B2 summarizes the processes included in the CO<sub>2</sub> land models presented in this work, as these  
1009 processes are seen for the moment as the main cause of discrepancies between estimates shown in all the previous  
1010 figures. According to Table B2, no bottom-up model or dataset used here contains all of the 13 LULUCF categories  
1011 reported in the NGHGIs. A simple analysis of the mean 1990-2020 LULUCF fluxes from the EU27+UK NGHGI  
1012 (Table A3 in Appendix A2) shows that six categories account for almost 90 % of the gross flux: Forest land remaining  
1013 forest land (56 %), Land converted to cropland (7 %), Land converted to forest land (7 %), Grassland remaining  
1014 grassland (6 %), Harvested wood products (6 %), and Land converted to settlements (6 %). DGVMs currently include  
1015 more of these categories than other methods. As shown in Fig. 8, the mean 1990-2019 value of the mean of the 15  
1016 TRENDY DGVM simulations is -81.9 Tg C yr<sup>-1</sup> (with a range of [-285,118] Tg C yr<sup>-1</sup>), while those of the  
1017 ORCHIDEE and CABLE-POP simulations using the high-resolution forcing provided in the VERIFY project are -



1018 171 Tg C yr<sup>-1</sup> and -84.8 Tg C yr<sup>-1</sup>, respectively. The means agree quite well for TRENDYv10 and CABLE-POP, but  
1019 the spread of all the DGVMs is quite large. In addition, the number of categories included may not be a good proxy  
1020 for quality of comparison. While an ideal model would include all categories in the NGHGI, it must also represent  
1021 these categories well. Figures 4-7 suggest that sector-specific models currently show better agreement with the  
1022 NGHGI than DGVMs, although a more detailed analysis including the entire suite of TRENDY models would be  
1023 insightful. Note that these **categories** are used as input to top-down approaches, and therefore cannot be disaggregated  
1024 into results after the simulation.

### 1025 3.3.6. Uncertainties in top-down and bottom-up estimates

1026 Uncertainties are essential for complete comparisons between models and approaches. This section  
1027 summarizes the main sources of uncertainty estimates interwoven throughout the above text. We also provide a  
1028 comparison of available uncertainties between the previous synthesis (V2019) and the current synthesis (V2021) for  
1029 both bottom-up and top-down methods. Finally, we give an overview of two important advances in uncertainty  
1030 estimation included in this work (one for the NGHGI, and one for top-down approaches), referring the interested  
1031 reader to the Appendix for more information.

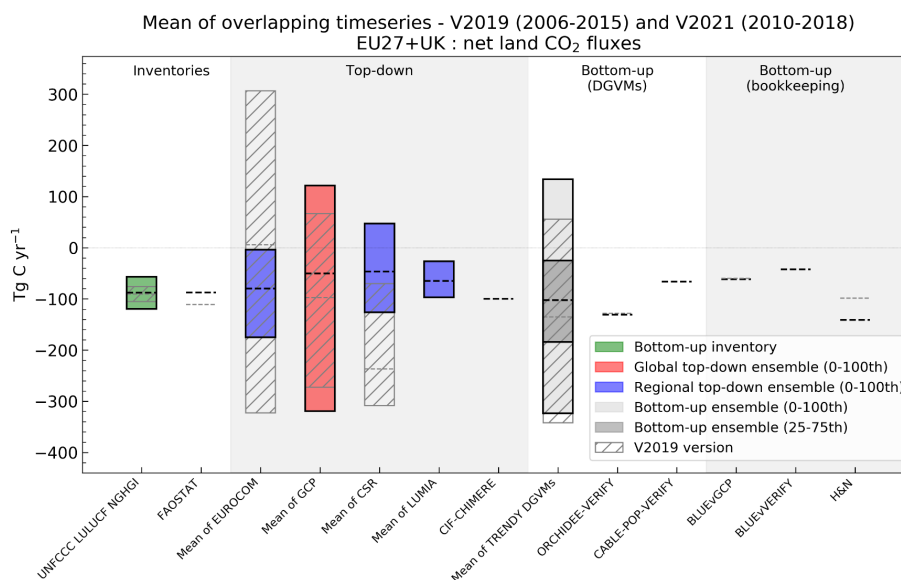
1032 Several sources of uncertainty arise from the synthesis of bottom-up (BU) inventories and models of carbon  
1033 fluxes, which can be summarized as: (a) differences due to input data and structural/parametric uncertainty of models  
1034 (Houghton et al., 2012) and (b) differences in definitions (Pongratz et al., 2014; Grassi et al., 2018b, 2021; Petrescu  
1035 et al., 2020, 2021b). **Posterior uncertainties** in top-down (TD) estimates mostly come from: 1) errors in the modeled  
1036 atmospheric transport; 2) aggregation errors, i.e., errors arising from the way the flux variables are discretized in space  
1037 and time and error correlations in time; 3) **errors in the background mole fractions**; and 4) incomplete information  
1038 from the observations and hence the dependence on the prior fluxes.

1039 Figure 10 summarizes the quantifiable uncertainties in this work, compared to previous results from Petrescu  
1040 et al. (2021b). With the exception of the NGHGI, all the other uncertainties are calculated from ensembles of  
1041 simulations using either: 1) multiple models of the same general type, either using model-specific inputs or attempting  
1042 to harmonize inputs as much as possible (e.g., TRENDY), or 2) multiple simulations with the same model, varying  
1043 input parameters and/or forcing data (e.g., CarboScopeRegional, LUMIA). As a complete characterization of model  
1044 uncertainty involves exploring the full parameter, input data, and model structure space, none of the uncertainties  
1045 reported here can be considered “complete”, but they represent best estimates given realistic constraints of resources  
1046 and knowledge. The uncertainties represent the mean of overlapping periods for the previous V2019 (overlapping  
1047 period: 2006-2015) versus the current V2021 (2010-2018). In general, the differences in mean behaviors between the  
1048 two versions falls within uncertainty estimates. Note, however, that this graph can hide certain behaviors. For  
1049 example, the similarity in the means for ORCHIDEE-VERIFY for both periods (-128.5 and -131.0 Tg C yr<sup>-1</sup> for V2019  
1050 and V2021, respectively) is likely a coincidence, given the wide fluctuation of annual values and the differences in  
1051 the multi-decadal means seen in Fig. 8.

1052 Figure 10 shows notable reductions in the spread of two ensembles: EUROCOM and CSR. Both of these  
1053 are regional ensembles. In addition, the CSR results show a weaker sink in the current V2021 version compared to  
1054 the previous V2019 version. As noted in Appendix A2, the change for CSR is explained by the inclusion of a corrected



1055 observation dataset for an isolated station in southeastern Europe which heavily influenced the regional results. The  
 1056 reduction in the spread of the EUROCOM ensemble results from the exclusion of a single member which produces  
 1057 annual flux results that are clear outliers compared to the remaining three members. More details of this analysis can  
 1058 be found in Appendix A2. The remaining ensembles retain similar model spread compared to the previous versions.



1059  
 1060 *Figure 10: Mean annual values of overlapping time periods (2006-2015) from Petrescu et al. (2021b) (transparent*  
 1061 *boxes and light gray lines) and new means for the 2010-2018 period from the current study (Fig. 8 and 9, Sect. 3.3.4*  
 1062 *and 3.3.5). The hashed boxes and colored boxes depict the “old” and “new” values for ensembles of multiple models,*  
 1063 *with the top and bottom of the boxes corresponding to minimum and maximum mean values of the overlapping period.*  
 1064 *For non-ensemble models (e.g., CIF-CHIMERE, FAOSTAT) the mean of the old and new overlapping periods are*  
 1065 *given by gray dotted and black dashed lines, respectively. The NGHGI UNFCCC uncertainty is calculated for*  
 1066 *submission year 2021 as the relative error of the NGHGI value, computed with the 95 % confidence interval method*  
 1067 *gap-filled and provided for every year of the timeseries. Inversions for both V2019 and V2021 have been corrected*  
 1068 *for emissions of CO<sub>2</sub> from lateral transport of carbon using identical datasets to enable a fair comparison. The fluxes*  
 1069 *follow the atmospheric convention, where negative values represent a sink while positive values represent a source.*

1071 Three advances in uncertainty estimation were made in this study, involving all three classes of models:  
 1072 NGHGI, bottom-up, and top-down. In Petrescu et al. (2021b), percentage uncertainties for the NGHGI (2019)  
 1073 LULUCF sector and land use categories were taken from reported uncertainties of the EU Member States and UK that  
 1074 are used for compiling the National Inventory Reports (NIR) of the EU27+UK bloc, as well as the aggregate  
 1075 uncertainties for the block reported in the EU NIR. Uncertainty estimates were only given for a single year and were



1076 also partially incomplete due to missing uncertainty estimates for some sectors/subsectors of some countries. For the  
1077 current work, we use values compiled by the EU inventory team involving a recently developed procedure to  
1078 harmonize and gap-fill uncertainties reported by the Member States at the sector level (see EU NIR, 2021). Error  
1079 correlations are accounted for, in addition to year-to-year variations in sub-sectoral contributions to the overall  
1080 uncertainty. Extensive details are found in Appendix A1, and permit estimates of uncertainty on an annual basis, as  
1081 opposed to the single value used in the previous synthesis. Note, however, that this procedure was not applied to sub-  
1082 sectoral categories (FL, CL, and GL), for which values were taken directly from EU NIR (2021) and applied across  
1083 the whole timeseries. Synthesis plots created for individual countries and reported on the VERIFY website (VERIFY  
1084 Synthesis Plots, 2022) take percentages directly from the respective country's NIR.

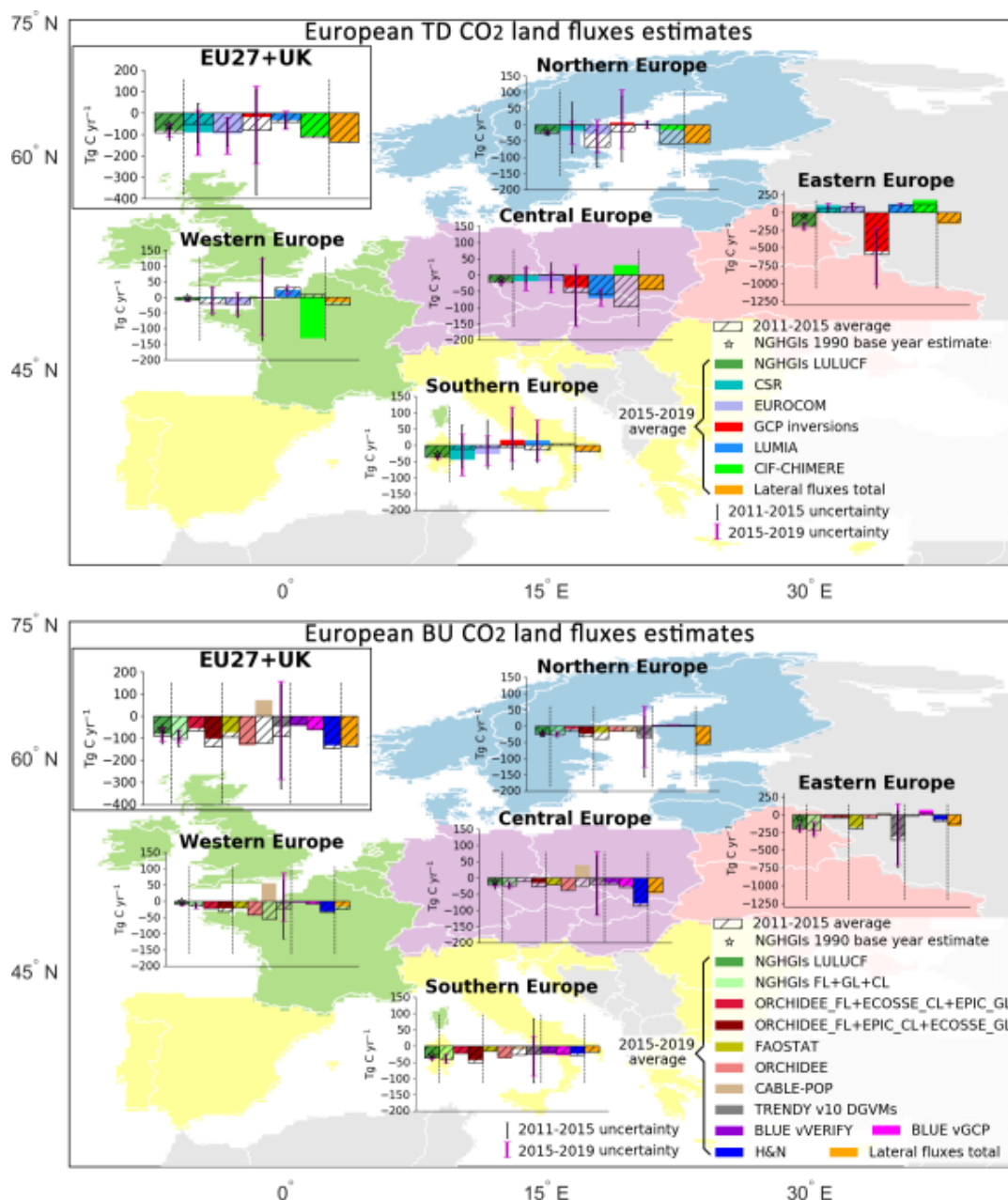
1085 The second advance relates to the impact of forcing data on bottom up models, in particular DGVMs. Figure  
1086 A3 (Appendix A) shows how the ORCHIDEE model responds to both changes in meteorological forcing (for  
1087 ORCHIDEE) and nitrogen forcing (for ORCHIDEE-N) over the past several decades. The impact of both is relatively  
1088 small compared to interannual variability. This is likely due to at least two reasons. The first reason is that  
1089 meteorological forcing used in this work has been re-aligned to the CRU observational dataset at 0.5 degrees and  
1090 monthly resolution, thus removing large-scale and long-term differences between the original meteorological datasets.  
1091 In addition, extensive spin-up and transient simulations are run for ORCHIDEE before reaching the point at which  
1092 the forcing changes (1981 for the meteorological forcing, and 1995 for the nitrogen forcing). Such lengthy simulations  
1093 enable woody biomass and soil carbon pools to develop a significant amount of inertia in response to additional  
1094 changes. Greater differences may be seen for models where modified forcing data covers the entire length of the pre-  
1095 production simulation steps.

1096 The final advance relates to uncertainty characterization in the regional inversion model CSR following the  
1097 methodology of Chevallier et al. (2007). Spatially explicit estimates of the uncertainty reduction achieved from the  
1098 flux optimization were prepared through a Monte Carlo approach using an ensemble of 40 members. The uncertainty  
1099 reduction is then calculated based on the ratio of the prior errors and the posterior spread of the ensemble members,  
1100 using a formula such that 0 indicates no reduction and 1 indicates a complete elimination of uncertainty. A preliminary  
1101 analysis showed that a considerable reduction may be achieved through the inclusion of more observation stations,  
1102 although additional work is needed. For the moment, these maps only reflect random uncertainties, and systematic  
1103 uncertainties remain poorly characterized. More information can be found in Appendix A2.

1104 Figure 11 presents an idea of the spatial uncertainties associated with these datasets. Total CO<sub>2</sub> land fluxes  
1105 from EU27+UK and five main regions in Europe are presented, divided into top-down (top panel) and bottom-up  
1106 (bottom panel) approaches for clarity. The regions (North, West, Central, East and South) consist of Annex I Parties  
1107 to UNFCCC both inside and outside of the EU27+UK bloc, and are listed in Table A1. Figure 11 shows the total CO<sub>2</sub>  
1108 land fluxes from the NGHGs for base year 1990, as well as five-year mean values for the 2011-2015 and 2015-2019  
1109 periods. The five-year periods are used as an exercise for what could be achieved in the first GST and also because  
1110 they provided the most overlap with the datasets reported here. As the BU models in VERIFY include and simulate  
1111 CO<sub>2</sub> fluxes for at most three out of the six classes reported to the UNFCCC (FL, CL and GL), for comparison and  
1112 consistency purposes both UNFCCC total LULUCF (including all six classes and HWP), as well as the UNFCCC



1113 FL+CL+GL estimates are shown. Figure 11 presents CO<sub>2</sub> fluxes that include both direct and indirect LULUCF effects  
1114 on managed land. The total UNFCCC estimates include the total LULUCF emissions and sinks (by the UNFCCC  
1115 definition) belonging to all six IPCC land classes and the HWP class (see Sect. 2.3 and Appendix B for more details).  
1116 The NGHGI estimates are plotted and compared against fluxes simulated with statistical global and regional datasets:  
1117 bookkeeping models, biosphere and sector-specific models, and inversion model ensembles. The error bar represents  
1118 the variability in model estimates as the min and max values in the ensemble.  
1119



1120  
 1121 **Figure 11:** Five-year means (2011–2015 and 2015–2019 as hashed and colored bars, respectively) of total CO<sub>2</sub> land  
 1122 flux estimates (in Tg C) for EU27+UK and five European regions (North, West, Central, South and East) for top-  
 1123 down (top) and bottom-up (bottom) methods compared to inventories. Eastern European region does not include  
 1124 European Russia. Northern Europe includes Norway. Central Europe includes Switzerland. The UNFCCC  
 1125 uncertainty for the Republic of Moldova was not available. The data comes from: UNFCCC NGHGI (2021) total





1126 *LULUCF submissions (dark green) which are plotted with respective base year 1990 (black star) estimates, the*  
1127 *UNFCCC NGHGI (2021) FL+CL+GL estimates (light green), sector-specific BU models for FL, CL and GL (CBM,*  
1128 *EPIC-IIASA, ECOSSE), ecosystem models (ORCHIDEE, TRENDY v10 DGVMs, CABLE-POP), global dataset*  
1129 *FAOSTAT, bookkeeping models (BLUE (vGCP, and vVERIFY) and H&N), total CO<sub>2</sub> flux from TD inversion*  
1130 *ensembles (GCP2021, EUROCOM) and three regional European inversions (CarboScopeReg (CSR), LUMIA and*  
1131 *CIF-CHIMERE). ECOSSE\_GL data was not updated beyond 2018. Lateral CO<sub>2</sub> fluxes (rivers/lakes, wood and*  
1132 *crops sinks/sources) are represented separately (orange) and are removed from the top-down estimates as explained*  
1133 *in the text. The fluxes follow the atmospheric convention, where negative values represent a sink while positive*  
1134 *values represent a source.*

1135 In general across the regions, BU (observation-based and process-based models) agree well with the  
1136 UNFCCC-reported total LULUCF sources and sinks, except for the CABLE-POP DGVM which simulates a source  
1137 for Central and Western Europe. As can be seen from the figure, however, this is not unexpected; the ensemble of  
1138 TRENDY DGVMs shows a very large spread, and as such some DGVMs will undoubtedly display more extreme  
1139 behavior. There remain however large disagreements between all estimates for Eastern Europe. This could be related  
1140 to reduced data coverage for this region, in particular for the top-down approaches which depend on atmospheric  
1141 measurement stations. In Northern Europe, some inversions agree with the NGHGIs on the magnitude of the sink  
1142 (mean of 2015-2019 of -65 Tg C yr<sup>-1</sup>), while in Central Europe there is a large variance between the models. The  
1143 differences are explained by updates and methodological changes detailed in Sect. 3.3.2 (sector specific process-based  
1144 models and NGHGI), 3.3.3 (DGVMs, bookkeeping models and NGHGI) and 3.3.4 (all BU, TD and NGHGI). Finally,  
1145 the TD estimates are better in line with the NGHGI and the BU estimates after the removal of emissions due to lateral  
1146 fluxes of carbon (discussed in Sect. 3.3.4). However, large variations still remain in the range of min/max of model  
1147 ensembles represented in the figure by the error bars. For some models with high inter-annual variability (e.g., CIF-  
1148 CHIMERE and CABLE-POP), the five-mean changes drastically between the two time periods but this may not  
1149 represent a significant trend.

1150

#### 1151 **4. Data availability**

1152 Annual timeseries for the EU27+UK used in creation of the figures in this work for V2019 and V2021 are  
1153 available for public download at <https://doi.org/10.5281/zenodo.7365863> (McGrath et al., 2022). **This excludes CO<sub>2</sub>**  
1154 **fossil data for the IEA, which is subject to license restrictions.** The data are reachable with one click (without the need  
1155 for entering login and password), and downloadable with a second click, consistent with the two click access principle  
1156 for data published in ESSD (Carlson and Oda, 2018). The data and the DOI number are subject to future updates and  
1157 only refers to this version of the paper. In addition, figures and annual timeseries for EU27+UK as well as other  
1158 countries and regions are available from VERIFY Synthesis Plots (2022).

1159

#### 1160 **5. Summary and concluding remarks**

1161 This work represents an update of the Petrescu et al. (2021b) European CO<sub>2</sub> synthesis paper presenting and  
1162 investigating differences between the UNFCCC NGHGI, BU data-based inventories, both coarse and high resolution





1163 process-based BU models, and TD approaches represented by both global and regional inversions. Datasets used in  
1164 the previous work have been updated by extending the temporal coverage and updating the models and data behind  
1165 the calculations. In addition, several new models to expand the number of independent approaches compared have  
1166 been added. Additional efforts have been made to improve uncertainty characterization in two approaches, along with  
1167 a first attempt to present as many datasets as possible in a clear single figure to draw overarching conclusions.

1168 CO<sub>2</sub> fossil emissions dominate the anthropogenic CO<sub>2</sub> flux in the EU27+UK, regardless of the approach  
1169 employed and irrespective of uncertainties. Fossil CO<sub>2</sub> emissions are more straightforward to estimate than ecosystem  
1170 fluxes **due to combustion being easier to model and parameterize at large scales**. A suite of eight BU methods for  
1171 fossil CO<sub>2</sub> emissions are within the uncertainty of the NGHGI when methods are harmonized to include similar  
1172 categories. The remaining differences can often be attributed to definitions, assumptions about activity data or  
1173 emission factors, and the allocation of fuel types to different sectors (see Sect. 3.2 and Fig. B3). The one available TD  
1174 method, a regional European inversion system (CIF-CHIMERE) using an NO<sub>x</sub> proxy to determine CO<sub>2</sub> fossil  
1175 emissions, shows broad agreement with the BU estimates. However, this initial TD inversion is not yet capable of  
1176 distinguishing the minor differences between the various BU estimates **and does not yet quantify uncertainties**.  
1177 However, a substantial decrease in the level of uncertainty of the inverse modeling system is expected in the near-  
1178 term with the large-scale deployment of observation networks dedicated to detecting fossil fuel emissions (e.g., with  
1179 launch of the CO<sub>2</sub>M<sup>19</sup> satellite mission in 2025). In the short-term, the CoCO<sub>2</sub> project (CoCO<sub>2</sub>, 2022) aims to advance  
1180 methodology around co-assimilation of existing CO<sub>2</sub> satellite data (from the OCO-2/3 instruments) and to provide  
1181 new analysis of the CO/FFCO<sub>2</sub> and NO<sub>x</sub>/FFCO<sub>2</sub> ratios in order to significantly decrease uncertainty in the fossil CO<sub>2</sub>  
1182 estimates.

1183 The CO<sub>2</sub> land fluxes belong to the LULUCF sector, which is one of the most uncertain sectors in UNFCCC  
1184 reporting. The IPCC guidelines prescribe methodologies that are used to estimate the CO<sub>2</sub> fluxes in the NGHGI, **but**  
1185 **grant countries significant freedom to adopt methods appropriate to their national circumstances**. When analyzing the  
1186 different estimates from multiple BU sources (inventories and models) similar sources of uncertainties are observed  
1187 such as: (a) differences due to input data and structural/parametric uncertainty of models (Houghton et al., 2012;  
1188 Pongratz et al., 2021) and (b) differences in definitions (Pongratz et al., 2014; Grassi et al., 2018b; Petrescu et al.,  
1189 2020, 2021b; Grassi et al., 2021). Reducing uncertainties in LULUCF estimates is needed given the increasing  
1190 importance of the sector to EU climate policy over the next decades. In contrast to **the previous 2020 climate and**  
1191 **energy package**, the LULUCF sector will now formally contribute to the binding emission reduction targets of the  
1192 Unions 2030 climate and energy framework (EU, 2018a; 2018b). Furthermore, the European Climate Law explicitly  
1193 states that LULUCF, together with all sectors of the economy, should contribute to achieving **Climate** neutrality within  
1194 the Union by 2050 (EU, 2021b).

1195 The LULUCF sector in NGHGIs is composed of six land use categories. Of these, Forest land provides the  
1196 most important contribution to the net CO<sub>2</sub> land flux in the EU27+UK, followed by Cropland and Grassland. HWP  
1197 and “Land converted to settlements” also have non-negligible contributions, and changes in HWP strongly influence

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<sup>19</sup> CO<sub>2</sub>M: Copernicus Anthropogenic Carbon Dioxide Monitoring,  
[https://esamultimedia.esa.int/docs/EarthObservation/CO2M\\_MRD\\_v3.0\\_20201001\\_Issued.pdf](https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf)



1198 variations in decennial mean net LULUCF fluxes for the region. Of these, all except “Land converted to settlements”  
1199 are represented in general ecosystem models, while Forestland, Cropland, and Grassland are simulated by sector-  
1200 specific process-based and data-driven models. Top-down inversions are capable of simulating net CO<sub>2</sub> fluxes to the  
1201 atmosphere, but cannot yet attribute them between different categories.

1202 Differences in the detailed sector-specific and inversion model results (Fig. 4-9) often come from choices in  
1203 the simulation setup and the type of model used: bookkeeping models, process-based DGVMs, inventory-based  
1204 statistical methods, or atmospheric inversions. Results also differ based on whether fluxes are attributed to LULUCF  
1205 emissions due to the cause or location of occurrence. For example, **indirect fluxes** on managed land are included in  
1206 NGHGI and FAOSTAT, while **additional sink capacity** (e.g., Petrescu et al., 2021b) is included in estimates from  
1207 process-based models (e.g., ORCHIDEE or TRENDY DGVMs). The use of gross land use changes fluxes (e.g., in  
1208 the NGHGI, bookkeeping models, and CABLE-POP) as opposed to net fluxes also likely plays an important role. We  
1209 found that adjusting top-down models by emissions/removals resulting from **later** transport of carbon through trade  
1210 and the inland water network improves the agreement with the NGHGI of the EU27+UK (Fig. 9, compared to Petrescu  
1211 et al., 2021b).

1212 **Observation-based BU estimates** of LULUCF provide large year-to-year flux variability (Fig. 4-7, in  
1213 particular for DGVMs like ORCHIDEE, CABLE-POP and the TRENDY ensemble), contrary to the NGHGI,  
1214 primarily due to the effect of varying meteorology. In particular, the duration and intensity of the summer growing  
1215 season can vary significantly between years (e.g., Bastos et al., 2020a; Thompson et al., 2020). In the framework of  
1216 periodic NGHGI assessments, the choice of a reference period (such as 2015-2019, as used here) or the use of a  
1217 moving window to calculate the means may be critical to smooth out high inter-annual variability and facilitate  
1218 comparisons. One can also imagine incorporating IAV into the NGHGIs through the use of annual anomalies of  
1219 emission factors calculated from Tier 3 observation-based approaches (either BU or TD). TD estimates also show  
1220 **very large inter-annual variability** (Fig. 9). Uncertainties in the inversion results are primarily due to uncertainties in  
1221 atmospheric transport modeling, boundary conditions, technical simplifications and uncertainty inherent to the  
1222 limitation of the observation network. **Currently, regional inversions (LUMIA, CSR and EUROCOM) are still under**  
1223 **development and face different challenges from the coarser resolution global systems used here to represent regional**  
1224 **results (GCP).** Based on this work, it is difficult to claim that one or the other provides a more accurate result for the  
1225 net CO<sub>2</sub> land fluxes across the EU27+UK, although two regional inversion ensembles (EUROCOM and CSR)  
1226 dramatically reduced their uncertainties between the previous and current versions of this synthesis, with CSR showing  
1227 much more overlap now with the NGHGI (Fig. 10).

1228 Uncertainties can be reflected in space as well as in time. Fig. 11 separates mean BU and TD values for all  
1229 methods into five different regions in Europe. From this figure, it's clear that some regions suffer from higher  
1230 uncertainties than others. Part of this is likely linked to the sparseness of atmospheric observation data for the TD  
1231 estimates (e.g., Eastern Europe). Reconciling differences across aggregated EU regions may be challenging due to  
1232 diverse methodologies and drivers in each country. On the other hand, the analysis of smaller regions or individual  
1233 countries may represent a productive first step towards monitoring the current state of emissions as national data and  
1234 experts can be used to help clarify differences across models. Country-level case studies may help inform the design



1235 of future monitoring and verification systems (MVS) for CO<sub>2</sub> which aim to supply additional evidence for the  
1236 emissions levels and trends, coupling anthropogenic activities and associated emissions with the atmospheric patterns  
1237 of greenhouse gas concentrations, and perform data assimilation and modeling over a wide variety of environmental  
1238 conditions (Pinty et al., 2017).

1239 As seen in figures throughout this work, reducing uncertainties of both individual models and classes of  
1240 models remains a priority. Some categories (Forestland, Cropland) produce results for multiple category-specific  
1241 models which lie within the uncertainty of the NGHGI. This likely reflects ~~relatively~~ the use of data-driven models  
1242 and the relatively high quality of data that is available due to the economic importance of these categories. On the  
1243 other hand, generalized ecosystem models (the DGVMs, like ORCHIDEE and CABLE-POP) may create mean  
1244 estimates which fall within uncertainties, but fall outside of NGHGI uncertainties for any given year due to the  
1245 sensitivity of processes in these models to rapidly changing meteorology and the necessity for these models to operate  
1246 globally, including in data-poor regions for which parameterization may be impossible. Two advances in  
1247 characterizing uncertainty were presented here: one for the case of the NGHGI, and one for the case of the TD model  
1248 CSR. Additional characterization of uncertainty both within and across models will enable more fair comparisons  
1249 between methods.

1250 A more detailed analysis of LULUCF fluxes at the regional/country level is foreseen as part of projects linked  
1251 to VERIFY including the RECCAP2 initiative (RECCAP2, 2022) and current and future Horizon Europe funded  
1252 projects (e.g., CoCO<sub>2</sub>, EYE-CLIMA, AVENGERS, PARIS) which will highlight examples of good practice in  
1253 LULUCF flux monitoring amongst European countries. Sect. 3.3.6 presents a summary of uncertainties to provide  
1254 insight into ground observation systems assimilated by inversions. This lays the basis of future improvements for  
1255 establishing best practices on how to configure atmospheric inversions and systematically quantify uncertainties. For  
1256 the overall estimation of emissions from LULUCF activities on all land types (Fig. 8), the comparison is made more  
1257 challenging as results from both land use and land use changes are presented. Comparing only the “effect of land use  
1258 change” (conversion) is non-trivial. A methodology for reconciling LULUCF country estimates from the FAOSTAT  
1259 datasets with the NGHGIs is presented in Grassi et al. (2022a) and Grassi et al. (in prep) for the global scale.

1260 The next steps needed to improve and facilitate the reconciliation between BU and TD estimates are the same  
1261 as those discussed in Petrescu et al. (2021b): 1) BU process-based models incorporating unified protocols and  
1262 guidelines for uniform definitions should be able to disaggregate their estimates to facilitate comparison to NGHGI  
1263 and 2006 IPCC practices (e.g., managed vs. unmanaged land, 20-year legacy for classes remaining in the same class,  
1264 distinction of fluxes arising solely from land use change, Grassi et al. (2022a)); 2) for sector-specific models, in  
1265 particular for cropland and grassland, improving treatment of the contribution of soil organic carbon dynamics to  
1266 the budget; 3) for TD estimates, using the recently developed Community Inversion Framework (Berchet et al., 2021)  
1267 to better assess the different sources of uncertainties from the inversion set-ups (model transport, prior fluxes,  
1268 observation networks), 4) standardize methods to compare datasets with and without interannual variability, and 5)  
1269 develop a clear way to report key system boundary, data, or definitional issues, as it often necessary to have deep  
1270 understanding of each estimate to know how to do a like-for-like comparison.



1271 Similar to Petrescu et al. (2021b), this updated study concludes that a complete, ready-for-purpose monitoring  
1272 system providing annual carbon fluxes across Europe is still under development, but data sources are beginning to  
1273 show improved agreement compared to previous estimates. Therefore, significant effort must still be undertaken to  
1274 reduce the uncertainty across all potential methods (i.e., structural uncertainty in the models as well as the input data  
1275 supplied to the models or inventory approaches) used in such a system (e.g. Maenhout et al., 2020). Future activities  
1276 in the CoCO<sub>2</sub> project (CoCO<sub>2</sub>, 2022) will investigate the one and five-year carbon budgets across the data-rich area  
1277 of the EU27+UK and deepen the analysis for both global and regional/local (city level) estimates.

1278 Achieving the well-below 2°C temperature goal of the Paris Agreement requires, among other things, low-  
1279 carbon energy technologies, forest-based mitigation approaches, and engineered carbon dioxide removal (Grassi et  
1280 al., 2018a; Nabuurs et al. 2017). Currently, the EU27+UK reports a sink for LULUCF and forest management will  
1281 continue to be the main driver affecting the productivity of European forests for the next decades (Koehl et al., 2010),  
1282 shown as well by the domination of Forestland CO<sub>2</sub> fluxes to the LULUCF sector in the NGHGI for the bloc. Forest  
1283 management changes forest composition and structure, which affects the exchange of energy with the atmosphere  
1284 (Naudts et al., 2016), and therefore the potential of mitigating climate change (Luyssaert et al., 2018; Grassi et al.,  
1285 2019). Meteorological extremes can also affect the efficiency of the sink (Thompson et al., 2020). The EU forest sink  
1286 is projected to decrease in the near future (Vizzari et al., 2021). Consequently, for the EU to meet its ambitious climate  
1287 targets, it is necessary to maintain and even strengthen the LULUCF sink (EU, 2020). Understanding the evolution of  
1288 the CO<sub>2</sub> land fluxes is critical to enable the EU27+UK to meet its ambitious climate goals.

1289

## 1290 **6. Appendices**

1291

### 1292 ***Appendix A: Data sources, methodology and uncertainty descriptions***

1293 Plots for all countries in Europe as well as dozens of country groups and some countries outside of Europe are available  
1294 following a simple registration (VERIFY Synthesis Plots, 2022).

1295

#### 1296 **VERIFY project**

1297 VERIFY's primary aim is to develop scientifically robust methods to assess the accuracy and potential biases  
1298 in national inventories reported by the parties through an independent pre-operational framework. The main concept  
1299 is to provide observation-based estimates of anthropogenic and natural GHG emissions and sinks as well as associated  
1300 uncertainties. The proposed approach is based on the integration of atmospheric measurements, improved emission  
1301 inventories, ecosystem data, and satellite observations, and on an understanding of processes controlling GHG fluxes  
1302 (ecosystem models, GHG emission models).

1303 Two complementary approaches relying on observational data-streams were combined in VERIFY to  
1304 quantify GHG fluxes:

1305 1) atmospheric GHG concentrations from satellites and ground-based networks (top-down atmospheric inversion  
1306 models) and



1307 2) bottom-up activity data (e.g., fuel use and emission factors) and **ecosystem measurements (bottom-up models)**.

1308 For CO<sub>2</sub>, a specific effort was made to separate fossil fuel emissions from ecosystem fluxes.

1309

1310 The objectives of VERIFY were:

1311 **Objective 1.** Integrate the efforts between the research community, national inventory compilers, operational centers  
 1312 in Europe, and international organizations towards the definition of future international standards for the verification  
 1313 of GHG emissions and sinks based on independent observation.

1314 **Objective 2.** Enhance the current observation and modeling ability to accurately and transparently quantify the sinks  
 1315 and sources of GHGs in the land-use sector for the tracking of land-based mitigation activities.

1316 **Objective 3.** Develop new research approaches to monitor anthropogenic GHG emissions in support of the EU  
 1317 commitment to reduce its GHG emissions by 40 % by 2030 compared to the year 1990.

1318 **Objective 4.** Produce periodic scientific syntheses of observation-based GHG balance of EU countries and practical  
 1319 policy-oriented assessments of GHG emission trends, and apply these methodologies to other countries.

1320

1321 For more information on the project team and products/results please visit the VERIFY website (VERIFY, 2022).

1322

1323 Table A1: *Country grouping used for comparison purposes between BU and TD emissions as reported for the*  
 1324 *country- and regional-level synthesis plots available through the VERIFY web portal.*

Country name – geographical Europe	BU-ISO3	Aggregation from TD-ISO3
Luxembourg	LUX	
Belgium	BEL	BENELUX
Netherlands	NLD	BNL
Bulgaria	BGR	BGR
Switzerland	CHE	
<i>Lichtenstein</i>	<i>LIE</i>	<i>CHL</i>
Czech Republic	CZE	Former Czechoslovakia
Slovakia	SVK	CSK
Austria	AUT	AUT
Slovenia	SVN	North Adriatic countries
Croatia	HRV	NAC
Romania	ROU	ROU
Hungary	HUN	HUN
Estonia	EST	



Lithuania	LTU	Baltic countries
Latvia	LVA	BLT
Norway	NOR	NOR
Denmark	DNK	
Sweden	SWE	
Finland	FIN	DSF
Iceland	ISL	ISL
Malta	MLT	MLT
Cyprus	CYP	CYP
France (Corsica incl.)	FRA	FRA
<i>Monaco</i>	<i>MCO</i>	
<i>Andorra</i>	<i>AND</i>	
Italy (Sardinia, Vatican incl.)	ITA	ITA
<i>San Marino</i>	<i>SMR</i>	
United Kingdom (Great Britain + N Ireland)	GBR	UK
<i>Isle of Man</i>	<i>IMN</i>	
Iceland		
Ireland	IRL	IRL
Germany	DEU	DEU
Spain	ESP	IBERIA
Portugal	PRT	IBE
Greece	GRC	GRC
<i>Russia (European part)</i>	<i>RUS European</i>	
<i>Georgia</i>	<i>GEO</i>	<i>RUS European+GEO</i>
<i>Russian Federation</i>	<i>RUS</i>	<i>RUS</i>
Poland	POL	POL
<i>Turkey</i>	<i>TUR</i>	<i>TUR</i>
EU27+UK (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Latvia, Luxembourg,	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GRC, HRV, HUN, IRL.	E28



Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden, United Kingdom)	ITA, LTU, LVA, LUX, MLT, NDL, POL, PRT, ROU, SVN, SVK, SWE, GBR	
Western Europe (Belgium, France, United Kingdom, Ireland, Luxembourg, Netherlands)	BEL, FRA, UK, IRL, LUX, NDL	WEE
Central Europe (Austria, Switzerland, Czech Republic, Germany, Hungary, Poland, Slovakia)	AUT, CHE, CZE, DEU, HUN, POL, SVK	CEE
Northern Europe (Denmark, Estonia, Finland, Lithuania, Latvia, Norway, Sweden)	DNK, EST, FIN, LTU, LVA, NOR, SWE	NOE
<i>South-Western Europe (Spain, Italy, Malta, Portugal)</i>	<i>ESP, ITA, MLT, PRT</i>	<i>SWN</i>
<i>South-Eastern Europe (all) (Albania, Bulgaria, Bosnia and Herzegovina, Cyprus, Georgia, Greece, Croatia, Macedonia, the former Yugoslav, Montenegro, Romania, Serbia, Slovenia, Turkey)</i>	<i>ALB, BGR, BIH, CYP, GEO, GRC, HRV, MKD, MNE, ROU, SRB, SVN, TUR</i>	<i>SEE</i>
<i>South-Eastern Europe (Albania, Bosnia and Herzegovina, Macedonia, the former Yugoslav, Georgia, Turkey, Montenegro, Serbia)</i>	<i>ALB, BIH, MKD, MNE, SRB, GEO, TUR</i>	<i>SEA</i>
<i>South-Eastern Europe (EU) (Bulgaria, Cyprus, Greece, Croatia, Romania, Slovenia)</i>	<i>BGR, CYP, GRC, HRV, ROU, SVN</i>	<i>SEZ</i>
<i>Southern Europe (all) (SOE) (Albania, Bulgaria, Bosnia and Herzegovina, Cyprus, Georgia, Greece, Croatia, Macedonia, the former Yugoslav, Montenegro, Romania, Serbia, Slovenia, Turkey, Italy, Malta, Portugal, Spain)</i>	<i>ALB, BGR, BIH, CYP, GEO, GRC, HRV, MKD, MNE, ROU, SRB, SVN, TUR, ITA, MLT, PRT, ESP</i>	<i>SOE</i>
<i>Southern Europe (SOY) Albania, Bosnia and Herzegovina, Georgia, Macedonia, the former Yugoslav, Montenegro, Serbia, Turkey)</i>	<i>ALB, BIH, GEO, MKD, MNE, SRB, TUR,</i>	<i>SOY</i>
Southern Europe (EU) (SOZ) (Bulgaria, Cyprus, Greece, Croatia, Romania, Slovenia, Italy, Malta, Portugal, Spain)	BGR, CYP, GRC, HRV, ROU, SVN, ITA, MLT, PRT, ESP	SOZ
Eastern Europe (Belarus, Moldova, Republic of, Russian Federation, Ukraine)	BLR, MDA, RUS, UKR	EAE
<i>EU-15 (Austria, Belgium, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Sweden)</i>	<i>AUT, BEL, DEU, DNK, ESP, FIN, FRA, GBR, GRC, IRL, ITA, LUX, NDL, PRT, SWE</i>	<i>E15</i>
<i>EU-27 (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Latvia, Luxembourg,</i>	<i>AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GRC, HRV,</i>	<i>E27</i>





<i>Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden)</i>	<i>HUN, IRL, ITA, LTU, LVA, LUX, MLT, NDL, POL, PRT, ROU, SVN, SVK, SWE</i>	
<i>All Europe (Aaland Islands, Albania, Andorra, Austria, Belgium, Bulgaria, Bosnia and Herzegovina, Belarus, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Faroe Islands, United Kingdom, Guernsey, Greece, Croatia, Hungary, Isle of Man, Ireland, Iceland, Italy, Jersey, Liechtenstein, Lithuania, Luxembourg, Latvia, Moldova, Republic of, Macedonia, the former Yugoslav, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Svalbard and Jan Mayen, San Marino, Serbia, Slovakia, Slovenia, Sweden, Turkey, Ukraine)</i>	<i>ALA, ALB, AND, AUT, BEL, BGR, BIH, BLR, CHE, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO, GBR, GGY, GRC, HRV, HUN, IMN, IRL, ISL, ITA, JEY, LIE, LTU, LUX, LVA, MDA, MKD, MLT, MNE, NDL, NOR, POL, PRT, ROU, RUS, SJM, SMR, SRB, SVK, SVN, SWE, TUR, UKR</i>	EUR

1325 \*countries highlighted in *italic* are not discussed in the current 2021 synthesis mostly because unavailability of UNFCCC NGHGI reports (non-  
 1326 Annex I countries<sup>20</sup>) but are present on the web-portal (VERIFY Synthesis Plots, 2022). Results for Annex I countries (NOR, CHE, ISL) and  
 1327 Eastern European countries (EAE) are represented in Fig. 11.

<sup>20</sup>Non-Annex I countries are mostly developing countries. The reporting to UNFCCC is implemented through national communications (NCs) and biennial update reports (BURs): <https://unfccc.int/national-reports-from-non-annex-i-parties>



1328

1329

1330 **Table A2:** Methodological changes (**in bold**) of the current study with respect to Petrescu et al. (2020), Petrescu et al.

1331 (2021b) and an internal VERIFY update (v2020); n/a cells mean that there is no data available.

1332

Publication year	Bottom-up anthropogenic CO <sub>2</sub> estimates (fossil CO <sub>2</sub> )			Top-down fossil CO <sub>2</sub> estimates	Bottom-up natural CO <sub>2</sub> (NBP) emissions/removals (land CO <sub>2</sub> )			Top-down land CO <sub>2</sub> emissions		Uncertainty and other changes
	Inventories	Global databases	Emission models		Inventories	Emission models	Global Databases	Regional models	Global models	
Petrescu et al. (2020) AFOLU bottom-up synthesis	n/a	n/a	n/a	n/a	National emissions from UNFCCC (2018) 1990-2016  <i>LULUCF Forest land</i> , - EU28 data for five years (1995, 2000, 2005, 2010 and 2015)  <i>Cropland and Grassland</i> (1990, 2005, 2010 and 2016)  <i>All land uses</i> EU28 timeseries 1990-2016	CBM Forest land (2000, 2005, 2010 and 2015)  EFISCEN Forest land (1995, 2000, 2005, 2010 and 2015)  BLUE All land uses 1990-2017  H&N All land uses 1990-2015  DGVMs (TRENDY v6) All land uses 1990-2017	FAOSTAT Timeseries Remaining and conversions 1990-2016	n/a	n/a	UNFCCC (2018) uncertainty estimates for 2016 (error propagation 95 % interval method)
Petrescu et al., 2021b	National emissions from UNFCCC	EDGAR v5.0 BP	n/a	IAP RAS fast-track inversion	National emissions from UNFCCC (2019)	CBM Forest land Timeseries	FAOSTAT Timeseries	CSR 2006-2018	GCP 2019 inversions 2000-2018	UNFCCC (2019) uncertainty estimates for 2016 (error propagation)



<p>(2019) CRFs                  2014                  All anthropogenic (excl. LULUCF) sectors, timeseries                  1990-2015</p>	<p>EIA                  CDIAC                  IEA                  GCP                  CEDS                  2014 estimates split by fuel type                  EDGAR v5.0                  All anthropogenic sectors, timeseries                  1990-2015</p>			<p>2014 (EU11+CHE)</p>	<p>1990-2017                  EU27 + UK timeseries                  of Forest Land, Cropland and Grassland                  Regional EU27 + UK totals (incl. NOR, CHE, UKR, MLD and BLR)</p>	<p>1990-2015                  EFISCEN                  Forest land timeseries                  2005-2018                  CO<sub>2</sub> emissions from inland waters                  ORCHIDEE                  Forest, cropland and grassland and all land uses                  1990-2018                  ECOSSE                  Cropland and grassland                  1990-2018                  EPIC-IIASA                  Cropland                  1990-2018                  BLUE                  All land uses                  1990-2018                  H&amp;N                  All land uses                  1990-2015                  DGVMs (TRENDY v7)                  All land uses</p>	<p>Remaining and conversions                  1990-2017</p>	<p>EUROCOM                  2006-2015</p>		<p>95 % interval method)                  For model ensembles reported as variability in extremes (min/max)</p>
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						1990-2018				
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<b>This study</b>	National emissions from UNFCCC (2021) CRFs 2017 All anthropogenic (excl. LULUCF) sectors, timeseries 1990-2019 All anthropogenic sectors, timeseries 1990-2018	EDGAR v6.0 BP EIA CDIAC IEA GCP CEDS <b>PRIMAP-hist 2.3</b> UNFCCC NGHGI <b>2021</b> 2017 estimates split by fuel type EDGAR v6.0 All anthropogenic sectors, timeseries 1990-2018	n/a	<b>CIF-CHIMERE fast-track inversion 2005-2020 (EU27+UK)</b>	National emissions from UNFCCC (2021) 1990-2019 EU27 + UK of Forest land	CBM Historical flux timeseries from Forest land remaining forest land 2000-2015 and new <b>2017-2020 estimate</b> <b>EFISCEN-SPACE (updated model)</b> Forest land timeseries 2005-2020 <b>For 15 EU countries</b> ORCHIDEE Forest, cropland and grassland and all land uses, <b>model updated</b> 1990-2020 <b>CABLE-POP 1990-2020</b> <b>BLUE-VERIFY and BLUE-GCP)</b> All land uses 1990-2019, 1990-2020 H&N <b>GCP2021</b> All land uses 1990-2020 DGVMs (TRENDY v10)	FAOSTAT timeseries Remaining and conversions 1990-2019	CarboScope Reg 2006-2020 EUROCOM 2009-2018 LUMIA 2006-2020 CIF-CHIMERE 2005-2020	<b>GCP 2021</b> inversions 2010-2020	UNFCCC (2021) uncertainty estimates for <b>2019</b> (error propagation 95 % interval method) For model ensembles reported as the annual extremes (min/max)
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						Forest, cropland and grassland and all land uses  1990-2020  ECOSSE  Cropland 1990-2020 Grassland 1990-2018  EPIC-IIASA Cropland 1990-2020 Grassland 1990-2020				
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1333

1334

1335 **A1: Fossil CO<sub>2</sub> emissions**

1336 ***Bottom-up emission estimates***

1337 For further details of all datasets, see Andrew (2020).

1338

1339 ***UNFCCC NGHGI (2021)***

1340 Annex I NGHGIs should follow principles of transparency, accuracy, consistency, completeness and  
 1341 comparability (TACCC) under the guidance of the UNFCCC (UNFCCC, 2014) and as mentioned above, shall be  
 1342 completed following the 2006 IPCC guidelines (IPCC, 2006). In addition, the IPCC 2019 Refinement (IPCC, 2019),  
 1343 which may be used to complement the 2006 IPCC guidelines, has updated sectors with additional emission sources  
 1344 and provides guidance on the use of atmospheric data for independent verification of GHG inventories.

1345 Both approaches (BU and TD) provide useful insights on emissions from two different points of view. First,  
 1346 as outlined in Volume 1, Chapter 6 of the 2019 IPCC Refinement (IPCC, 2019), TD approaches act as an additional  
 1347 quality check for BU and NGHGI approaches, and facilitate a deeper understanding of the processes driving changes  
 1348 in different elements of GHG budgets. Second, while independent BU methods do not follow prescribed standards  
 1349 like the IPCC Guidelines, they do provide complementary information based on alternative input data at varying  
 1350 temporal, spatial, and sectoral resolution. This complementary information helps build trust in country GHG estimates,



1351 which form the basis of national climate mitigation policies. Additionally, BU estimates are needed as input for TD  
1352 estimates. As there is no formal guideline to estimate uncertainties in TD or BU approaches, uncertainties are usually  
1353 assessed from the spread of different estimates within the same approach, though some groups or institutions report  
1354 uncertainties for their individual estimates using a variety of methods, for instance, by performing Monte Carlo  
1355 sensitivity simulation by varying input data parameters. However, this can be logistically and computationally difficult  
1356 when dealing with complex process-based models.

1357 Despite the important insights gained from complementary BU and TD emission estimates, it should be noted  
1358 that comparisons with the NGHGI are not always straightforward. BU estimates often share common methodology  
1359 and input data, and through harmonization, structural differences between BU estimates and NGHGIs can be  
1360 interpreted. **However, the use of common input data restricts the independence between the datasets and, from a**  
1361 **verification perspective, may limit the conclusions drawn from the comparisons.** On the other hand, TD estimates are  
1362 constrained by independent atmospheric observations and can serve as an additional, **nearly independent** quality check  
1363 for NGHGIs. Nonetheless, structural differences between NGHGIs (what sources and sinks are included, and where  
1364 and when emissions/removals occur) and the actual fluxes of GHGs to the atmosphere must be taken into account  
1365 during comparison of estimates. While NGHGIs go through a central QA/QC review process, the UNFCCC reporting  
1366 requirements do not mandate large-scale observation-derived verification. Nevertheless, the individual countries may  
1367 use atmospheric data and inverse modeling within their data quality control, quality assurance and verification  
1368 processes, with expanded and updated guidance provided in chapter 6 of the 2019 Refinement of IPCC 2006  
1369 Guidelines (IPCC, 2019). So far, only a few countries (e.g. Switzerland, UK, New Zealand and Australia) have used  
1370 atmospheric observations to constrain national emissions and documented these verification activities in their national  
1371 inventory reports (Bergamaschi et al., 2018), and none do so for CO<sub>2</sub>.

1372 Under the UNFCCC convention and its Kyoto Protocol, national greenhouse gas (GHG) inventories are the  
1373 most important source of information to track progress and assess climate protection measures by countries. In order  
1374 to build mutual trust in the reliability of GHG emission information provided, national GHG inventories are subject  
1375 to standardized reporting requirements, which have been continuously developed by the Conference of the Parties  
1376 (COP)<sup>21</sup>. The calculation methods for the estimation of greenhouse gasses in the respective sectors is determined by  
1377 the methods provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These  
1378 Guidelines provide detailed methodological descriptions to estimate emissions and removals, as well as  
1379 recommendations to collect the activity data needed. As a general overall requirement, the UNFCCC reporting  
1380 guidelines stipulate that reporting under the Convention and the Kyoto Protocol must follow the five key principles  
1381 of transparency, accuracy, completeness, consistency and comparability (TACCC).

1382 The reporting under UNFCCC shall meet the TACCC principles. The three main GHGs are reported in  
1383 timeseries from 1990 up to two years before the due date of the reporting. The reporting is strictly source category  
1384 based and is done under the Common Reporting Format tables (CRF), downloadable from the UNFCCC official  
1385 submission portal: <https://unfccc.int/ghg-inventories-annex-i-parties/2021>.

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<sup>21</sup> The last revision has been made by COP 19 in 2013 (UNFCCC, 2013)





1386           The UNFCCC NGHGI CO<sub>2</sub> emissions/removals include estimates from five key sectors for the EU27+UK:  
1387   1 Energy, 2 Industrial processes and product use (IPPU), 3 Agriculture, 4 LULUCF and 5 Waste. The tiers method a  
1388   country applies depends on the national circumstances and the individual conditions of the land, which explains the  
1389   variability of uncertainties among the sector itself as well as among EU countries. This annual published dataset  
1390   includes all CO<sub>2</sub> emissions sources for those countries, and for most countries for the period 1990 to t-2. Some eastern  
1391   European countries' submissions began in the 1980s.

1392

### 1393   *NGHGI uncertainties*

1394           The presented uncertainties in the reported emissions of the individual countries and the EU27+UK bloc  
1395   were calculated by using the methods and data used to compile the official GHG emission uncertainties that are  
1396   reported by the EU under the UNFCCC (NIRs, 2022). The EU uncertainty analysis reported in the bloc's National  
1397   Inventory Report (NIR) is based on country-level, Approach 1 uncertainty estimates (IPCC, 2006, Vol. 1, Chap. 3)  
1398   that are reported by EU Member States, Iceland and United Kingdom under Article 7(1)(p) of EU (2013). These  
1399   country-level uncertainty estimates are typically reported at beginning of a submission cycle and are not always  
1400   revised with updated CRF submissions later in the submission cycle. Furthermore, the compiled uncertainties of some  
1401   countries are incomplete (e.g., uncertainties not estimated for LULUCF and/or indirect CO<sub>2</sub> emissions, certain  
1402   subsector emissions are confidential) and the sector and gas resolution at which uncertainties are provided varies  
1403   between the countries. The EU inventory team therefore implements a procedure to harmonize and gap-fill these  
1404   uncertainty estimates. A processing routine reads the individual country uncertainty files that are pre-formatted  
1405   manually to assign consistent sector and gas labels to the respective estimates of emissions/removals and uncertainties.  
1406   The uncertainty values are then aggregated to a common sector resolution, at which the emissions and removals  
1407   reported in the uncertainty tables of the countries are then replaced with the respective values from the final CRF  
1408   tables of the countries. Due to the issue of incompleteness mentioned above, the country-level data are then screened  
1409   to identify residual GHG emissions and removals for which no uncertainty estimates have been provided. Where  
1410   sectors are partially complete, the residual net emission is quantified in CO<sub>2</sub> equivalents and incorporated. An  
1411   uncertainty is then estimated, by calculating the overall sector uncertainty of the sources and sinks that were included  
1412   in that country's reported uncertainties estimates and assigning this percentage average to the residual net emission.  
1413   In cases where for certain sectors no uncertainties have been provided at all (e.g., indirect CO<sub>2</sub> emissions, LULUCF),  
1414   an average (median) sector uncertainty in percent is calculated from all the countries for which complete sectoral  
1415   emissions and uncertainties were reported, and this average uncertainty is assigned to the country's sector GHG total  
1416   reported in its final CRF tables.

1417           The country-level uncertainties presented in this paper, have been compiled using this same processing  
1418   routine and using the uncertainties and CRF data reported by the countries in the 2021 submission. However, here the  
1419   method has been expanded to gap-fill at the individual greenhouse gas level (CO<sub>2</sub> emissions and removals only) rather  
1420   than at the aggregate GHG level. Furthermore, the expanded method here assigns the sub-sectoral uncertainties to the  
1421   emissions and removals of the entire timeseries (1990-2019), rather than just the base year and latest year of the  
1422   respective timeseries. This allows uncertainties to be sensitive to the sub-sectoral contributions to sectoral and national



1423 total emissions, which of course change over time. For each year of the timeseries, uncertainties in the total and  
1424 sectoral CO<sub>2</sub> emissions are calculated using Gaussian error propagation, by summing the respective sub-sectoral  
1425 uncertainties (expressed in kt CO<sub>2</sub>) in quadrature and assuming no error correlation. In contrast, for the EU27+UK  
1426 bloc, uncertainties in the total and sectoral CO<sub>2</sub> emissions were calculated to take into account error correlations  
1427 between the respective country estimates at the subsector level. This was done by applying the same methods and  
1428 assumptions described in the 2022 EU NIR (UNFCCC NIR, 2022). The subsector resolution applied for gap-filling  
1429 allows the routine to access respective data on emission factors from CRF Table *Summary 3* and apply correlation  
1430 coefficients ( $r$ ) when aggregating the uncertainties. For a given subsector, it is assumed that the errors of countries  
1431 using default factors are completely correlated ( $r = 1$ ), while errors of countries using country-specific factors are  
1432 assumed uncorrelated ( $r = 0$ ). For countries using a mix of default and country-specific factors at the given subsector  
1433 level, it is assumed that these errors are partially correlated ( $r = 0.5$ ) with one another and with the errors of countries  
1434 using the default factors only.

1435 Based on these correlation assumptions, the routine then aggregates CO<sub>2</sub> emissions/removals and  
1436 uncertainties for the specified subsector resolution at the EU27+UK level. Uncertainties at sector total level are then  
1437 aggregated from the subsector estimates assuming no correlation between subsectors. However, for countries reporting  
1438 very coarse resolution estimates (e.g., total sector CO<sub>2</sub> emissions/removals) or where the sector has been partially or  
1439 completely gap-filled, it is assumed that these uncertainties are partially correlated ( $r = 0.5$ ) with one another and with  
1440 the other reported subsector level estimates. Level uncertainties on the total EU27+UK CO<sub>2</sub> emissions and removals  
1441 (with and without LULUCF) are then aggregated from the sector estimates assuming no error correlation between  
1442 sectors.

1443 Note that the above procedure does not apply to LULUCF categories (FL, CL, and GL). Estimates for these  
1444 values were taken directly from the EU NIR (2021 without gap-filling or consideration of correlations. As the values  
1445 are given for only one single year, this value is applied uniformly across the whole timeseries.

#### 1446 ***EDGAR v6.0***

1447 The first edition of the Emissions Database for Global Atmospheric Research was published in 1995. The  
1448 dataset now includes almost all sources of fossil CO<sub>2</sub> emissions, is updated annually, and reports data for 1970 to year  
1449  $n-1$ . Estimates for v6.0 are provided by sector. Emissions are estimated fully based on statistical data from 1970 till  
1450 2018 <https://data.jrc.ec.europa.eu/dataset/97a67d67-c62e-4826-b873-9d972c4f670b>.

1451 **Uncertainties:** EDGAR uses emission factors (EFs) and activity data (AD) to estimate emissions. Both EFs and AD  
1452 are uncertain to some degree, and when combined, their uncertainties need to be combined too. To estimate EDGAR's  
1453 uncertainties (stemming from lack of knowledge of the true value of the EF and AD), the methodology devised by  
1454 IPCC (2006, Chapter 3) is adopted, **that is the overall uncertainty is the square root of the sum of squares of the**  
1455 **uncertainty of the EF and AD (uncertainty of the product of two variables)**. A log-normal probability distribution  
1456 function is assumed in order to avoid negative values, and uncertainties are reported as the 95 % confidence interval  
1457 according to IPCC (2006, chapter 3, equation 3.7). For emission uncertainty in the range 50 % to 230 % a correction



1458 factor is adopted as suggested by Frey et al. (2003) and IPCC (2006, chapter 3, equation 3.4). Uncertainties are  
1459 published in Solazzo et al. (2021).

#### 1460 ***BP***

1461 BP releases its Statistical Review of World Energy annually in June, the first report being published in 1952.  
1462 Primarily an energy dataset, BP also includes estimates of fossil-fuel CO<sub>2</sub> emissions derived from its energy data (BP  
1463 2011, 2017). The emissions estimates are totals for each country starting in 1965 to year n-1.

#### 1464 ***CDIAC***

1465 The original Carbon Dioxide Information Analysis Center included a fossil CO<sub>2</sub> emissions dataset that was  
1466 long known as CDIAC. This dataset is now produced at Appalachian State University, and has been renamed CDIAC-  
1467 FF (CDIAC, 2022). It includes emissions from **fossil fuels and cement production** from 1751 to year n-3. Fossil-fuel  
1468 emissions are derived from UN energy statistics, and cement emissions from USGS production data.

#### 1469 ***EIA***

1470 The US Energy Information Administration publishes **international energy statistics** and from these derives  
1471 estimates of energy combustion CO<sub>2</sub> emissions. Data are currently available for the period 1980-2016.

#### 1472 ***IEA***

1473 The International Energy Agency publishes international energy statistics and from these derives estimates  
1474 of energy combustion CO<sub>2</sub> emissions **including from the use of coal in the iron and steel industry**. Emissions estimates  
1475 start in 1960 for OECD members and 1971 for non-members, and run through n-1 for OECD members' totals, and  
1476 year n-2 for members' details and non-members. **Estimates are available by sector for a fee.**

#### 1477 ***GCP***

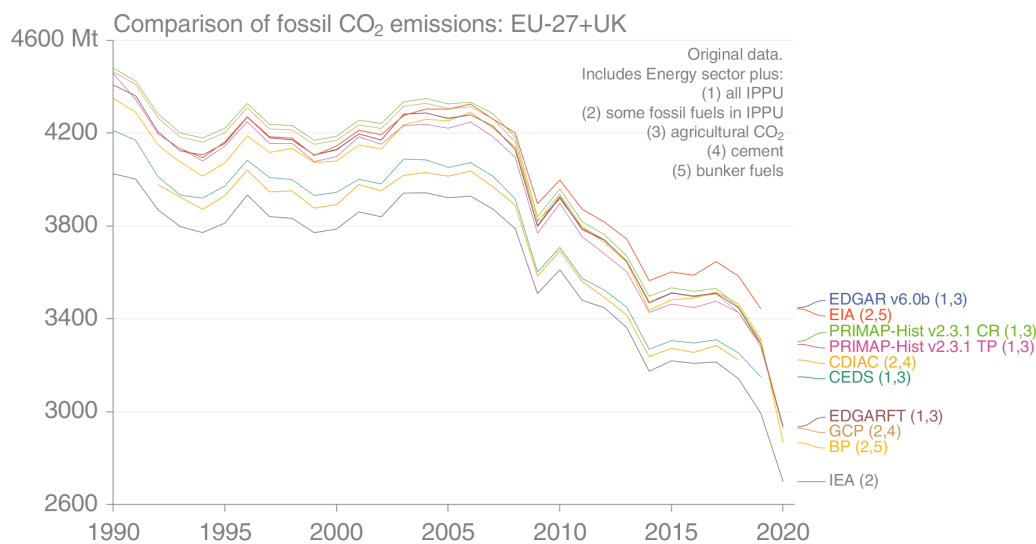
1478 The Global Carbon Project includes estimates of fossil CO<sub>2</sub> emissions in its annual Global Carbon Budget  
1479 publication. These include emissions from fossil fuels and cement production for the period 1750 to year n-1.

#### 1480 ***CEDS***

1481 The Community Emissions Data System has included estimates of fossil CO<sub>2</sub> emissions since 2018, with an  
1482 irregular update cycle (CEDS, 2022). Energy data are directly from IEA, but emissions are scaled to higher-priority  
1483 sources, including national inventories. Almost all emissions sources are included and estimates are published for the  
1484 period 1750 to year n-1. Estimates are provided by sector.

#### 1485 ***PRIMAPv2.2***

1486 The PRIMAP-hist dataset combines several published datasets to create a comprehensive set of greenhouse  
1487 gas emission pathways for every country and Kyoto gas, covering the years 1850 to 2018, and all UNFCCC (United  
1488 Nations Framework Convention on Climate Change) member states as well as most non-UNFCCC territories. The  
1489 data resolves the main IPCC (Intergovernmental Panel on Climate Change) 2006 categories. For CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O  
1490 subsector data for Energy, Industrial Processes and Product Use (IPPU), and Agriculture is available. Due to data  
1491 availability and methodological issues, version 2.2 of the PRIMAP-hist dataset does not include emissions from Land  
1492 Use, Land-Use Change, and Forestry (LULUCF). More info at <https://zenodo.org/record/4479172#.YUsc6p0zblU>.



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1493  
1494 *Figure A1: Comparison of EU27+UK fossil CO<sub>2</sub> emissions from multiple inventory datasets; Identical to Fig. 2,*  
1495 *except that no system boundaries harmonization has been done. CDIAC does not report emissions prior to 1992 for*  
1496 *former-Soviet Union countries. CRF: UNFCCC NGHGI from the Common Reporting Format tables.*

1497

1498

### 1499 ***Top-down CO<sub>2</sub> emission estimates***

### 1500 ***CIF-CHIMERE - fossil CO<sub>2</sub> emission inversion***

1501 CIF-CHIMERE is used for both CO<sub>2</sub> land and CO<sub>2</sub> fossil emission estimates, and this section only describes  
1502 the CO<sub>2</sub> fossil estimates. The product is explained in more detail by Fortems-Cheiney and Broquet, 2021.

1503 Results from previous atmospheric inversions of the European fossil CO<sub>2</sub> emissions indicated that there were  
1504 much larger uncertainties associated with the assimilation of CO data than with that of NO<sub>2</sub> data for such a purpose  
1505 (Konovalov et al, 2016; Konovalov and Llova, 2018). In this context, we have developed an atmospheric inversion  
1506 configuration quantifying monthly to annual budgets of the national emissions of fossil CO<sub>2</sub> in Europe based on the  
1507 assimilation of the long-term series of NO<sub>2</sub> spaceborne observations; the Community Inversion Framework (CIF); the  
1508 CHIMERE regional chemistry transport model (CTM); corrections to the TNO-GHGco-v3 inventory of NO<sub>x</sub>  
1509 anthropogenic emissions at 0.5° horizontal resolution; and the conversion of NO<sub>x</sub> anthropogenic emission estimates  
1510 into CO<sub>2</sub> fossil emission estimates. For the first time, to our knowledge, variational regional inversions have been  
1511 performed to estimate the European CO<sub>2</sub> fossil emissions **using NO<sub>x</sub> emissions from OMI satellite observations**.  
1512 Particular attention is paid in the analysis assessing the consistency between the fossil CO<sub>2</sub> emissions estimates from  
1513 our processing chain with the fossil CO<sub>2</sub> emission budgets provided by the TNO-GHGco-v3 inventory based on the



1514 emissions reported by countries to UNFCCC, which are assumed to be accurate in Europe. The algorithm first  
1515 optimizes NO<sub>x</sub> emissions and then assumes a fixed ratio of NO<sub>x</sub> to fossil CO<sub>2</sub> emissions. However, long-term plans  
1516 include the simultaneous inversion of all three gasses (CO<sub>2</sub>, NO<sub>2</sub>, and CO).

1517 The analysis is conducted over the period 2005 to 2020. CHIMERE is run over a 0.5°×0.5° regular grid and  
1518 17 vertical layers, from the surface to 200hPa, with 8 layers within the first two kilometers. The domain includes 101  
1519 (longitude) × 85 (latitude) grid-cells (15.25°W-35.75°E; 31.75°N-74.25°N) and covers Europe. CHIMERE is driven  
1520 by the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological forecast (Owens and  
1521 Hewson, 2018). The chemical scheme used in CHIMERE is MELCHIOR-2, with more than 100 reactions (Lattuati,  
1522 1997; CHIMERE 2017), including 24 for inorganic chemistry. Climatological values from the LMDZ-INCA global  
1523 model (Szopa et al., 2008) are used to prescribe concentrations at the lateral and top boundaries and the initial  
1524 atmospheric composition in the domain. Considering the short NO<sub>2</sub> lifetime, we do not consider its import from outside  
1525 the domain: its boundary conditions are set to zero. Nevertheless, we take into account peroxyacetyl nitrate (PAN)  
1526 and the associated NO<sub>x</sub> reservoir for the large-scale transport of NO<sub>x</sub>.

1527 Several critical aspects of this workflow need to be highlighted: (i) Fortems-Cheiney and Broquet (2021)  
1528 have not yet reported estimates of the uncertainty in the fossil CO<sub>2</sub> emissions (this requires the derivation of the  
1529 uncertainties in the NO<sub>x</sub> emission inversions and in the NO<sub>x</sub>-to-FFCO<sub>2</sub> emission conversion), and (ii) the fossil CO<sub>2</sub>  
1530 emission budgets provided by the TNO-GHGco-v3 inventory are based on the emissions reported by countries to  
1531 UNFCCC, which are assumed to be accurate in Europe, and therefore the NO<sub>x</sub> inversion prior estimate is consistent  
1532 with the inventory estimates (with respect to the NO<sub>x</sub>-to-FFCO<sub>2</sub> emission conversion used to infer fossil CO<sub>2</sub>  
1533 emissions from the NO<sub>x</sub> inversions).

1534 **Uncertainty:** There is no uncertainty estimate currently available for this product.

1535

## 1536 **A2: Land CO<sub>2</sub> emissions/removals**

### 1537 *Bottom-up CO<sub>2</sub> estimates*

#### 1538 *UNFCCC NGHGI 2021 - LULUCF*

1539 Under the convention and its Kyoto Protocol, national greenhouse gas (GHG) inventories are the most  
1540 important source of information to track progress and assess climate protection measures by countries. In order to  
1541 build mutual trust in the reliability of GHG emission information provided, national GHG inventories are subject to  
1542 standardized reporting requirements, which have been continuously developed by the Conference of the Parties  
1543 (COP)<sup>22</sup>. The calculation methods for the estimation of greenhouse gasses in the respective sectors is determined by  
1544 the methods provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). They  
1545 provide detailed methodological descriptions to estimate emissions and removals, as well as recommendations to

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<sup>22</sup>The last revision has been made by COP 19 in 2013 (UNFCCC, 2013)



1546 collect the activity data needed. As a general overall requirement, the UNFCCC reporting guidelines stipulate that  
 1547 reporting under the Convention and the Kyoto Protocol must follow the five key principles of transparency, accuracy,  
 1548 completeness, consistency and comparability (TACCC).

1549 The reporting under UNFCCC shall meet the TACCC principles. The three main GHGs are reported in  
 1550 timeseries from 1990 up to two years before the due date of the reporting. The reporting is strictly source category  
 1551 based and is done under the Common Reporting Format tables (CRF), downloadable from the UNFCCC official  
 1552 submission portal: <https://unfccc.int/ghg-inventories-annex-i-parties/2021>.

1553 For the biogenic CO<sub>2</sub> emissions from **sector 4 LULUCF**, methods for the estimation of CO<sub>2</sub> removals differ  
 1554 enormously among countries and land use categories. Each country uses its own country specific method which takes  
 1555 into account specific national circumstances (as long as they are in accordance with the 2006 IPCC guidelines), as  
 1556 well as IPCC default values, which are usually more **conservative** and result in higher uncertainties. The EU GHG  
 1557 inventory underlies the assumption that the individual use of national country specific methods leads to more accurate  
 1558 GHG estimates than the implementation of a single EU wide approach (UNFCCC, 2018b). Key categories for the  
 1559 EU27 are 4.A.1 Forest Land: Land Use CO<sub>2</sub>, 4.A.2. Forest Land: Land Use CO<sub>2</sub>, 4.B.1 Cropland Land Use CO<sub>2</sub>, 4.B.2  
 1560 Cropland Land Use CO<sub>2</sub>, 4.C.1 Grassland Land Use CO<sub>2</sub>, 4.C.2 Grassland Land Use CO<sub>2</sub>, 4.D.1 Wetlands Land Use  
 1561 CO<sub>2</sub>, 4.E.2 Settlements Land Use CO<sub>2</sub>, and 4.G Harvested Wood Production Wood product CO<sub>2</sub>. The tiered method  
 1562 a country applies depends on the national circumstances and the individual conditions of the land, which explains the  
 1563 variability of uncertainties among the sector itself as well as among EU countries.

1564 Table A3 shows the mean values of all LULUCF categories for the EU27+UK NGHGI (2021). The  
 1565 contribution is calculated as the percentage of the sum of the absolute values of all the categories, in order to account  
 1566 for differing signs.

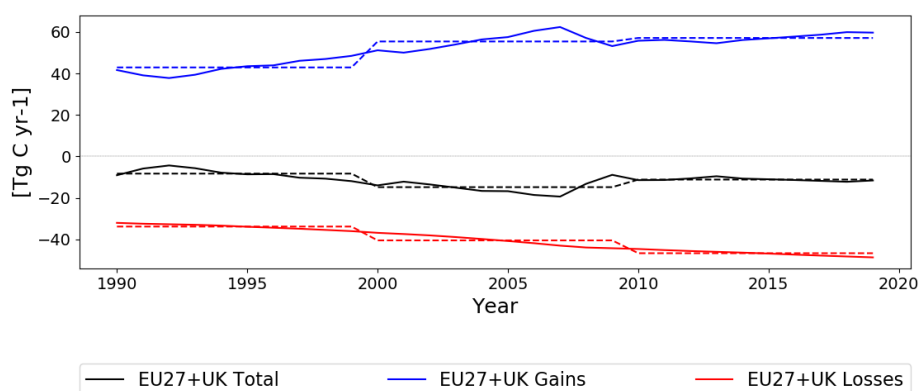
1567 *Table A3: LULUCF categories for the EU27+UK NGHGI (2021)*

Category	Mean value for 1990-2020 [Tg C]	Contribution to gross LULUCF flux [%]
Forest land remaining forest land	-107	56.0
Land converted to forest land	-13.0	6.80
Cropland remaining cropland	8.45	4.41
Land converted to cropland	14.0	7.33
Grassland remaining grassland	11.8	6.16
Land converted to grassland	-8.22	4.23
Wetlands remaining wetlands	2.89	1.51
Land converted to wetlands	1.09	0.567
Settlements remaining settlements	1.42	0.744
Land converted to settlements	11.8	6.15



Other land remaining other land	N/A	N/A
Land converted to other land	0.135	0.0706
Harvested wood products	-11.5	5.99

1568  
 1569



1570

1571 *Figure A2: The gains, losses, and total HWP pools from the Common Reporting Format tables for the European*  
 1572 *Union (Convention), which covers the EU27+UK. Dashed lines show the averages for 1990-1999, 2000-2009, and*  
 1573 *2010-2019 for easy comparison with Fig. 3.*

1574

1575 **Uncertainty:** Methodology for the NGHGI UNFCCC submissions are based on Chapter 3 of 2006 IPCC Guidelines  
 1576 for National Greenhouse Gas Inventories and is the same as described in Appendix A1.

1577

1578 **ORCHIDEE**

1579 ORCHIDEE is a general ecosystem model designed to be coupled to an atmospheric model in the context of  
 1580 modeling the entire Earth system. As such, ORCHIDEE calculates its prognostic variables (i.e., a multitude of C,  
 1581 H<sub>2</sub>O and energy fluxes) from the following environmental drivers: air temperature, wind speed, solar radiation, air  
 1582 humidity, precipitation and atmospheric CO<sub>2</sub> concentration. As the run progresses, vegetation grows on each pixel,  
 1583 divided into fifteen generic types (e.g., broadleaf temperate forests, C3 crops), which cycle carbon between the soil,  
 1584 land surface, and atmosphere, through such processes such as photosynthesis, litter fall, and decay. Limited human  
 1585 activities are included through the form of generic wood and crop harvests, which remove aboveground biomass on  
 1586 an annual basis. The version reported here, ORCHIDEE-N v3, includes a dynamic nitrogen cycle coupled to the



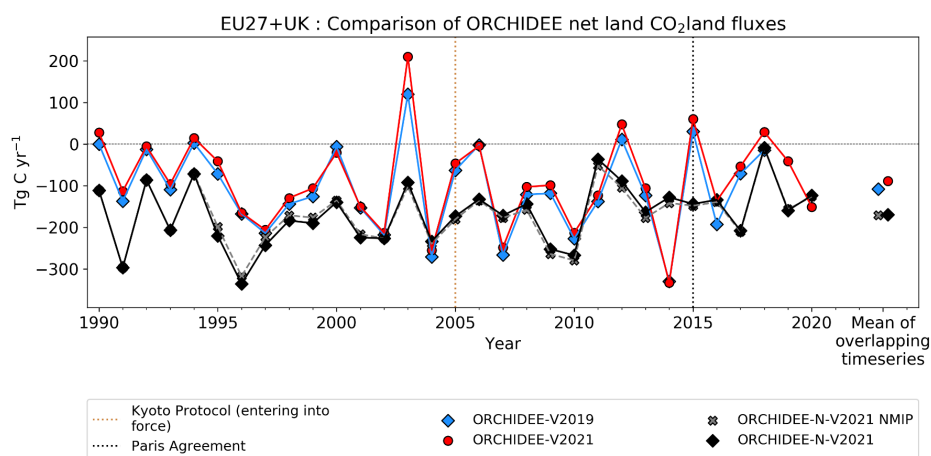


1587 vegetation carbon cycle which results in, among other things, limitations on photosynthesis in nitrogen-poor  
1588 environments (Vuichard et al., 2019)

1589 Among other environmental indicators, ORCHIDEE simulates positive and negative CO<sub>2</sub> emissions from  
1590 plant uptake, soil decomposition, and harvests across forests, grasslands, and croplands. Activity data is based on land  
1591 use and land cover maps. For VERIFY, pixel land cover/land use fractions were based on a combination of the land  
1592 use map LUH2v2h and the land cover project of the Climate Change Initiative (CCI) program of the European Space  
1593 Agency (ESA). The latter is based on purely remotely sensed methods, while the former makes use of national harvest  
1594 data from the U.N. Food and Agricultural Organization.

1595 **LUH2v2-ESACCI:** We describe here the input data and algorithms used to create the land cover maps specific for  
1596 our CMIP6 simulations using the historical/future reconstruction of land use states provided as reference datasets for  
1597 CMIP6 within the land use harmonization database LUH2v2h (Hurtt et al., 2020). More details are provided on the  
1598 devoted web page <https://orchidas.lscce.ipsl.fr/dev/lccc> which shows further tabular, graphical and statistical data. The  
1599 overall approach relies on the combination of the LUH2v2 data with present-day land cover distribution derived from  
1600 satellite observations for the past decades. The main task consists in allocating the land-use types from LUH2v2 in  
1601 the different PFTs for the historical period and the future scenarios. The natural vegetation in each grid cell is defined  
1602 as the PFT distribution derived from the ESA-CCI land cover product for the year 2010 to which pasture fraction and  
1603 crop fraction from LUH2v2 (for the year 2010) have been subtracted from grass and crop PFTs. This characterization  
1604 of the natural vegetation in terms of PFT distribution is assumed invariant in time and is used for both the historical  
1605 period and the different future scenarios” (Lurton et al., 2020).

1606



1607



1608 *Figure A3: A comparison of the version of ORCHIDEE used in previous synthesis of Petrescu et al. (2021b) compared*  
1609 *to the same version using the forcing prepared for this work (ORCHIDEE-V2021) and the version with the coupled*  
1610 *C-N cycle from this work (ORCHIDEE-N-V2021). For the current work, both the version shown with the Europe-*



1611 *specific nitrogen forcing prepared under VERIFY for the years 1995-2018 (ORCHIDEE-N-V2021) and that using the*  
1612 *standard nitrogen forcing from the N<sub>2</sub>O Model Intercomparison Project (NMIP; Tian et al., 2018) as supplied to the*  
1613 *TRENDY model intercomparison is shown (ORCHIDEE-N-V2021 NMIP).*

1614

1615 **Uncertainty:** In the ORCHIDEE model, uncertainty arises from three primary sources: parameters, forcing data  
1616 (including spatial and temporal resolution), and model structure. Some researchers argue that the initial state of the  
1617 model (i.e., the values of the various carbon and water pools at the beginning of the production run, following model  
1618 spinup) represents a fourth area. However, the initial state of this version of ORCHIDEE is defined by its equilibrium  
1619 state, and therefore a strong function of the parameters, forcing data, and model structure, with the only independent  
1620 choice being the target year of the initial state. Out of the three primary areas of uncertainty, the climate forcing data  
1621 is dictated by the VERIFY project itself, thus removing that source from explaining observed differences among the  
1622 models, although it can still contribute to uncertainty between the ORCHIDEE results and the national inventories.  
1623 The land use/land cover maps, another major source of uncertainty for ORCHIDEE carbon fluxes, have also been  
1624 harmonized to a large extent between the bottom-up carbon budget models in the project. Parameter uncertainty and  
1625 model structure thus represent the two largest sources of potential disagreement between ORCHIDEE and the other  
1626 bottom-up carbon budget models. Computational cost prevents a full characterization of uncertainty due to parameter  
1627 selection in ORCHIDEE (and dynamic global vegetation models in general), and uncertainties in model structure  
1628 require the use of multiple models of the same type but including different physical processes. Such a comparison has  
1629 not been done in the context of VERIFY, although the results from the TRENDY suite of models shown in Fig. 8 give  
1630 a good indication of this. Figure A3 shows a small influence from the nitrogen forcing, likely because the European  
1631 nitrogen forcing is only available from 1995-2018 and ORCHIDEE carries out almost 500 years of simulation prior  
1632 to this point. Many major carbon pools (i.e., woody biomass, soil carbon) have built up a large amount of inertia over  
1633 that time and are unlikely to undergo dramatic changes for any realistic forcing over the past. A similar conclusion  
1634 can be reached from simulations ORCHIDEE-V2019 and ORCHIDEE-V2021 in Fig. A3, which only differ in  
1635 meteorological forcing from 1981-2020.

1636

### 1637 **CABLE-POP**

1638 CABLE-POP (Haverd *et al.*, 2018) is a global terrestrial biosphere model developed around a  
1639 core biogeophysics module (Wang & Leuning, 1998) and a biogeochemistry module including cycles of nitrogen and  
1640 phosphorus (Wang *et al.*, 2010). Only nitrogen cycling was turned on for the present simulations. The model also  
1641 includes modules simulating woody demography (Haverd *et al.*, 2013) as well as land use change and land  
1642 management (Haverd *et al.*, 2018). The model distinguishes seven plant functional types which can co-occur in a  
1643 given grid cell. CABLE-POP does not simulate (natural) dynamic vegetation and the distribution and cover fraction  
1644 of PFTs is only affected by land use change. Forest demography (establishment, age class distribution, mortality) is  
1645 accounted for in the simulations, as are natural disturbances and forest management (wood harvest).

1646 For the simulations described here, a baseline land cover map was created from the HILDA+ dataset for the year 1901  
1647 and vegetation classes in the dataset were reclassified to correspond to PFTs represented in CABLE-POP. Land use



1648 transitions as well as land management (harvest) were prescribed from the LUH2v2h dataset over the entire simulation  
1649 period. Crops and pastures are treated as C3 grasses but are subject to agricultural harvest fluxes as given by LUH2v2h.  
1650 The use of HILDA+ data for the land cover distribution and the LUH2v2h for the representation of land cover/land  
1651 use change likely introduced additional uncertainties resulting from a potential mismatch between the two data sets.

1652

1653

#### 1654 *CO<sub>2</sub> Emissions from inland waters*

1655 In this study we did not update these estimates and they are therefore identical to those in Petrescu et al.  
1656 (2021b). These estimates represent a climatology of average annual CO<sub>2</sub> emissions from rivers, lakes and reservoirs  
1657 at the spatial resolution of 0.1°. The approach combines CO<sub>2</sub> evasion fluxes from the global river network, as estimated  
1658 by the empirical model of Lauerwald et al. (2015), with the lakes and reservoirs estimates by Hastie et al. (2019) for  
1659 the boreal biome and by Raymond et al. (2013) for the lower latitudes. The Lauerwald et al. and Hastie et al. studies  
1660 follow the same approach and rely on the development of a statistical prediction model for inland water pCO<sub>2</sub> at 0.5°  
1661 using global, high-resolution geodata. The pCO<sub>2</sub> climatology was then combined with different estimates of the gas  
1662 transfer velocity *k* to produce the resulting map of CO<sub>2</sub> evasion. The Raymond et al. study only provides mean flux  
1663 densities at the much coarser spatial resolution of the so-called COSCAT regions. All estimates were then downscaled  
1664 to 0.1° using the spatial distribution of European inland water bodies. Note that in contrast to Hastie et al. (2019), the  
1665 areal distribution of lakes was extracted from the HYDROLAKES database (Messenger et al., 2016), to be consistent  
1666 with the estimates of inland water N<sub>2</sub>O and CH<sub>4</sub> presented by Petrescu et al. (2021b).

1667 **Uncertainty:** Monte Carlo simulations were performed to constrain uncertainties resulting from both the pCO<sub>2</sub>  
1668 prediction equation and the choice of the *k* formulation.

1669

#### 1670 *CBM*

1671 The Carbon Budget Model developed by the Canadian Forest Service (CBM-CFS3), can simulate the  
1672 historical and future stand- and landscape-level C dynamics under different scenarios of harvest and natural  
1673 disturbances (fires, storms), according to the standards described by the IPCC (Kurz et al., 2009). Since 2009, the  
1674 CBM has been tested and validated by the Joint Research Centre of the European Commission (JRC), and adapted to  
1675 the European forests. It is currently applied to 26 EU Member States, both at country and NUTS2 level (Pilli et al.,  
1676 2016).

1677 Based on the model framework, each stand is described by area, age and land use classes and up to 10  
1678 classifiers based on administrative and ecological information and on silvicultural parameters (such as forest  
1679 composition and management strategy). A set of yield tables define the merchantable volume production for each  
1680 species while species-specific allometric equations convert merchantable volume production into aboveground  
1681 biomass at stand-level. At the end of each year the model provides data on the net primary production (NPP), carbon  
1682 stocks and fluxes, as the annual C transfers between pools and to the forest product sector.



1683 The model can support policy anticipation, formulation and evaluation under the LULUCF sector, and it is  
1684 used to estimate the current and future forest C dynamics, both as a verification tool (i.e., to compare the results with  
1685 the estimates provided by other models) and to support the EU legislation on the LULUCF sector (Grassi et al., 2018a).  
1686 In the biomass sector, the CBM can be used in combination with other models, to estimate the maximum wood  
1687 potential and the forest C dynamic under different assumptions of harvest and land use change (Jonsson et al., 2018).  
1688 **Uncertainty:** Quantifying the overall uncertainty of CBM estimates is challenging because of the complexity of each  
1689 parameter. The uncertainty in CBM arises from three primary sources: parameters, forcing data (including spatial and  
1690 temporal resolution) and model structure. It is linked to both activity data and emission factors (area, biomass volume  
1691 implied by species specific equation to convert the merchantable volume to total aboveground biomass (used as a  
1692 biomass expansion factor)) as well to the capacity of each model to represent the original values, in this case estimated  
1693 through the mean percentage difference between the predicted and observed values. A detailed description of the  
1694 uncertainty methodology is found in Pilli et al. (2017).

1695

1696 **Explanatory note on the extrapolation of Net Biome Productivity for the period 2017-2020** (Matteo Vizzarri,  
1697 Roberto Pilli, Giacomo Grassi, EC-JRC)

1698 *Background*

1699 We performed a linear extrapolation of forest Net Biome Productivity (NBP) by country (EU 25 Member States and  
1700 UK) in the period 2017-2020 based on the correlation between NBP and harvest from the period 2000-2015. Cyprus  
1701 and Malta are excluded from the analysis because of missing historical data.

1702 *Input data*

1703 Table A4 reports a summary of input data sources.

1704 *Table A4: main input data used in the extrapolation of NBP for the period 2017-2020.*

	Unit	Temporal resolution	Source
--	------	---------------------	--------



<b>Wood removals (HWP pool)</b>	t C	Annual (2000-2015)	CBM calibration run
<b>Forest area</b>	ha	Annual (2000-2020)	FAOSTAT <sup>23</sup>
<b>Roundwood amount</b>	m <sup>3</sup>	Annual (2000-2020)	FAOSTAT <sup>24</sup>
<b>NBP</b>	t C	Annual (2000-2015)	CBM calibration run

1705

1706 *Assessment procedure*

1707 The extrapolation of the NBP for the period 2017-2020 was obtained throughout the following steps:

- 1708 1. For each country (EU 25 Member States + UK), we first calculated the **average conversion factor** –  
 1709 representing a correspondence between one ton of biomass carbon removed and one cubic meter of wood per  
 1710 hectare – for the period 2000-2015 through equation [1]:

1711 
$$CF_{2000-2015} = \sum_{t=2000}^{2015} \frac{HWP_t}{RW_t A_{2015}} \quad \text{eq. (1)}$$

1712 where:  $CF_{2000-2015}$  is the average conversion factor per hectare in the period 2000-2015 (t C m<sup>-3</sup> ha<sup>-1</sup>);  
 1713  $HWP_t$  is the carbon content per ha in harvested wood products in year  $t$  (t C year<sup>-1</sup>), as derived from the CBM  
 1714 model run;  $RW$  is the total roundwood removals in year  $t$  (m<sup>3</sup> year<sup>-1</sup>) (source: FAOSTAT<sup>25</sup>);  $A_{2015}$  is the managed  
 1715 forest area in year 2015 (ha; source: Forest Europe 2015).

- 1716 2. Using the average conversion factor estimated in eq. 1, we converted, for each country, the total roundwood  
 1717 removals per ha derived from FAOSTAT for the period 2017-2020, to the corresponding amount of carbon  
 1718 removals per ha, through equation [2]:

1719 
$$HWP_{conv} = CF_{2000-2015} \cdot \left(\frac{RW_t}{A_{2015}}\right) [\forall t = 2017 \div 2020] \quad \text{eq. (2)}$$

1721 where:  $HWP_{conv}$  is the amount of carbon removals per hectare in year  $t$  (t C ha<sup>-1</sup> year<sup>-1</sup>);  $CF_{2000-2015}$  is the  
 1722 average conversion factor per hectare in the period 2000-2015 (t C m<sup>-3</sup> ha<sup>-1</sup>);  $RW_t$  is the total roundwood in year  $t$   
 1723 (m<sup>3</sup> year<sup>-1</sup>) (source: FAOSTAT<sup>26</sup>);  $A_{2015}$  is the managed forest area in the year 2015 (ha).

- 1724 3. Then, for each country and the period 2000-2015, we performed a **linear regression** to search for significant  
 1725 correlation between the harvest amount (i.e. HWP in t C ha<sup>-1</sup> yr<sup>-1</sup>) and NBP, according to the generalized  
 1726 equation:

1727 
$$NBP = a + b \cdot (HWP) \quad \text{eq. (3)}$$

1728 In this case, we assumed NBP as the dependent variable (t C ha<sup>-1</sup> year<sup>-1</sup>), the amount of harvest (t C ha<sup>-1</sup> year<sup>-1</sup>)  
 1729 as the main driver affecting the short term evolution of NBP, in absence of other exogenous natural  
 1730 disturbances;  $a$  is the intercept of the linear trendline;  $b$  is the coefficient of the independent variable harvest

<sup>23</sup> <https://www.fao.org/faostat/en/#data/RL>

<sup>24</sup> <https://www.fao.org/faostat/en/#data/FO>

<sup>25</sup> <https://www.fao.org/faostat/en/#data/FO>

<sup>26</sup> <https://www.fao.org/faostat/en/#data/FO>



1731 amount (i.e. HWP) ( $\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$ ). This approach is consistent with the methodological assumptions reported  
 1732 in Jonsson et al. (2021).

1733 4. We finally calculated the **NBP in the period 2017-2020** for each country through equation [4]:

1734 
$$NBP_{t,m} = (a + b \cdot HWP_{conv})_{t,m} \quad \text{eq. (4)}$$

1735 where:  $NBP_{t,m}$  is the Net Biome Productivity for year  $t$ , country  $m$  ( $\text{t C ha}^{-1} \text{year}^{-1}$ );  $a_{t,m}$  is the intercept  
 1736 of the linear trendline for year  $t$ , country  $m$ ;  $b_{t,m}$  is the coefficient of the independent variable in the trendline;  
 1737  $HWP_{conv(t,m)}$  is the amount of carbon removal per ha for year  $t$ , country  $m$  ( $\text{t C ha}^{-1} \text{year}^{-1}$ ).

1738 Forest area and parameters used in equation [4] by country are reported in Table A5.

1739 *Table A5: country-based forest area in 2015 and parameters used in equation [4]. \*: significant ( $p < 0.05$ ); NS: not*  
 1740 *significant ( $p > 0.05$ ).*

EU 25 + UK	CF (2000-2015)	Intercept (a)	Coefficient (b)	$p < 0.05$
<b>Austria</b>	0.28	2.60	-1.57	*
<b>Belgium</b>	0.18	2.97	-1.54	*
<b>Bulgaria</b>	0.22	1.17	-2.13	*
<b>Croatia</b>	0.28	1.42	-1.27	*
<b>Czechia</b>	0.22	2.55	-1.21	*
<b>Denmark</b>	0.16	1.92	-1.21	*
<b>Estonia</b>	0.20	1.16	-1.08	*
<b>Finland</b>	0.23	1.15	-1.20	*



<b>EU 25 + UK</b>	<b>CF (2000-2015)</b>	<b>Intercept (a)</b>	<b>Coefficient (b)</b>	<b><math>p &lt; 0.05</math></b>
<b>France</b>	0.19	1.63	-1.17	*
<b>Germany</b>	0.21	2.55	-1.23	*
<b>Greece</b>	0.20	1.17	-1.75	ns
<b>Hungary</b>	0.27	1.50	-1.54	*
<b>Ireland</b>	0.18	6.12	-5.45	*
<b>Italy</b>	0.23	0.69	0.39	ns
<b>Latvia</b>	0.19	2.00	-1.77	*
<b>Lithuania</b>	0.22	1.11	-0.89	*
<b>Luxembourg</b>	0.20	1.79	-1.40	*
<b>Netherlands</b>	0.22	2.44	-2.01	*
<b>Poland</b>	0.21	2.49	-2.16	*
<b>Portugal</b>	0.29	1.39	-1.01	*
<b>Romania</b>	0.32	1.54	-1.65	*
<b>Slovakia</b>	0.28	2.57	-1.42	*
<b>Slovenia</b>	0.24	2.07	-1.55	*
<b>Spain</b>	0.28	0.26	0.18	ns
<b>Sweden</b>	0.23	1.02	-1.20	*



EU 25 + UK	CF (2000-2015)	Intercept (a)	Coefficient (b)	$p < 0.05$
United Kingdom	0.19	2.27	-1.34	*

1741

1742 *Additional notes*

1743 Because of biased estimates, values for the year 2016 were excluded from this analysis.

1744 Extrapolated NBP for Czech Republic, Ireland and Netherlands were negative (thus showing emissions) because of  
1745 an increase of harvest in the corresponding years (2017-2020) compared to the previous period 2000-2015. Estonia  
1746 shows negative extrapolated NBP only for the year 2018.

#### 1747 *EFISCEN-Space*

1748 The European Forest Information SCENario Model (EFISCEN) is a large-scale forest model that projects  
1749 forest resource development on a regional to European scale. The model uses aggregated national forest inventory  
1750 data as a main source of input to describe the current structure and composition of European forest resources. The  
1751 model projects the development of forest resources, based on scenarios for policy, management strategies and climate  
1752 change impacts. With the help of biomass expansion factors, stem wood volume is converted into whole-tree biomass  
1753 and subsequently to whole tree carbon stocks. Information on litter fall rates, felling residues and natural mortality is  
1754 used as input into the soil module YASSO (Liski et al., 2005), which is dynamically linked to EFISCEN and delivers  
1755 information on forest soil carbon stocks. The core of the EFISCEN model was developed by Prof. Ola Sallnäs at the  
1756 Swedish Agricultural University (Sallnäs, 1990). It has been applied to European countries in many studies since then,  
1757 dealing with a diversity of forest resource and policy aspects. A detailed model description is given by Verkerk et al.  
1758 (2016), with online information on availability and documentation of EFISCEN at <http://efiscen.efi.int>. The model  
1759 and its source code are freely available, distributed under the GNU General Public License conditions  
1760 ([www.gnu.org/licenses/gpl-3.0.html](http://www.gnu.org/licenses/gpl-3.0.html)).

1761 In this report the follow-up of the EFISCEN model was used, called EFISCEN-Space (Schelhaas et al., in  
1762 prep). EFISCEN-Space simulates the development of the forest at the level of the plots as measured in the national  
1763 forest inventories, thereby providing a much higher spatial detail. The simulation is based on the distribution of trees  
1764 over diameter classes rather than age as in the old EFISCEN model. This allows the simulation of a wider variety of  
1765 stand structures, species mixtures and management options. Similar to the EFISCEN model, biomass expansion  
1766 factors and the YASSO soil carbon model are used to provide carbon balances for the forest. For use within VERIFY,  
1767 individual plot results are aggregated to a 0.125 degree grid. For the moment only 15 European member states are  
1768 included, partly due to the lack of an appropriate national forest inventory in the other member states, or because the  
1769 data could not be shared. No formal sensitivity and uncertainty analysis has been conducted yet.





1770 Figure 5 shows results which vary from year-to-year. In practice, the model was initialized with starting  
1771 years depending on the country, assuming that all data applied to this year. The model then produced stock and flux  
1772 changes for the subsequent five-year period, reporting a single mean value per pixel. To compute timeseries for the  
1773 EU27+UK, it was further assumed that these values were valid across 2005-2020. As the fluxes were given per square  
1774 meter of forest, they were scaled by the total area of the forest in each pixel found on the land use/land cover maps  
1775 used by the ORCHIDEE DGVM. This explains why the numbers vary from year to year; the flux per square meter of  
1776 forest does not change, but the total amount of forest area changes slightly. It should be noted that country-level values  
1777 available on the VERIFY website are only available for the five-year period for which the model produces a mean  
1778 result.

1779

1780 **Uncertainties:** A sensitivity analysis of EFISCEN v3 is described in detail in Chapter 6 of the user manual (Schelhaas  
1781 et al., 2007). Total sensitivity is caused by especially young forest growth, width of volume classes, age of felling and  
1782 few other variables. Scenario uncertainty comes on top of this when projecting in future. Within VERIFY, a full  
1783 uncertainty analysis has been completed, enabling the estimation of uncertainty ranges of the various output variables  
1784 (Schelhaas et al., 2020).

1785

#### 1786 ***EPIC-IIASA***

1787 The Environmental Policy Integrated Climate (EPIC) model is a field-scale process-based model (Izaurralde  
1788 et al., 2006; Williams, 1990) which calculates, with a daily time step, crop growth and yield, hydrological, nutrient  
1789 and carbon cycling, soil temperature and moisture, soil erosion, tillage, and plant environment control. Potential crop  
1790 biomass is calculated from photosynthetically active radiation using the radiation-use-efficiency concept modified for  
1791 vapor pressure deficit and atmospheric CO<sub>2</sub> concentration effect. Potential biomass is adjusted to actual biomass  
1792 through daily stress caused by extreme temperatures, water and nutrient deficiency, or inadequate aeration. The  
1793 coupled organic C and N module in EPIC (Izaurralde et al., 2006) distributes organic C and N between three pools of  
1794 soil organic matter (active, slow and passive) and two litter compartments (metabolic and structural). EPIC calculates  
1795 potential transformations of the five compartments as regulated by soil moisture, temperature, oxygen, tillage and  
1796 lignin content. Daily potential transformations are adjusted to actual transformations when the combined N demand  
1797 in all receiving compartments exceeds the N supply from the soil. The transformed components are partitioned into  
1798 CO<sub>2</sub> (heterotrophic respiration), dissolved C in leaching (DOC) and the receiving SOC pools. EPIC also calculates  
1799 SOC loss with erosion.

1800 The EPIC-IIASA (version EU) modeling platform was built by coupling the field-scale EPIC version 0810  
1801 with large-scale data on land cover (cropland and grasslands), soils, topography, field size, crop management practices  
1802 and grassland cutting intensity aggregated at a 1x1 km grid covering European countries (Balkovič et al., 2018, 2013).  
1803 In VERIFY, a total of 10 major European crops including winter wheat, winter rye, spring barley, grain maize, winter  
1804 rapeseed, sunflower, sugar beet, potatoes, soybean and rice were used to represent agricultural production systems in  
1805 European cropland. Crop fertilization and irrigation were estimated for NUTS2 statistical regions between 1995 and  
1806 2010 (Balkovič et al., 2013). For VERIFY, the simulations were carried out assuming conventional tillage, consisting



1807 of two cultivation operations and moldboard plowing prior to sowing and an offset disking after harvesting of cereals.  
1808 Two row cultivations during the growing season were simulated for maize and one ridging operation for potatoes. It  
1809 was assumed that 20 % of crop residues are removed in the case of cereals (excluding maize), while no residues are  
1810 harvested for other crops.

1811 A total of five managed grassland types with distinct temperature requirements, biomass productivity, and  
1812 phenology were used to represent the C-cycle in European grasslands. High-productive generic winter pasture and tall  
1813 fescue-based grasslands were used for Atlantic Europe, low fescue grasslands for the cool climates of Nordic regions  
1814 and high mountains, high-productive tall fescue-based grasslands and low-productive bluegrass types for continental  
1815 Europe, and low-productive bromegrass and high-productive winter pastures in the Mediterranean regions. Annual  
1816 nitrogen and carbon inputs, including inorganic and manure fertilization, and atmospheric N deposition, were obtained  
1817 from ISIMIP3 (Jägermeyr et al., 2021). In this dataset, the annual manure production and the fraction of manure from  
1818 livestock applied to cropland and rangeland were used from Zhang et al. (2017). The original manure data were re-  
1819 gridded to half-degree spatial resolution in ISMIP3. In the model, manure is applied as an organic fertilizer with a  
1820 C:N ration of 14.5:1. The organic carbon and nitrogen are added to the fresh organic litter pool where they decompose  
1821 in a manner identical to the fresh litter from vegetation, while mineral N from manure is added to the soil nitrate and  
1822 ammonium pools. The distribution of herbage biomass export intensity was constructed based on (Chang et al., 2016).  
1823 **Uncertainty:** In EPIC, uncertainties arise from three primary sources which were described in detail by ORCHIDEE.  
1824 A detailed sensitivity and uncertainty analysis of EPIC-IIASA regional carbon modeling is presented in (Balkovič et  
1825 al., 2020).

1826

### 1827 *ECOSSE (grasslands)*

1828 ECOSSE is a biogeochemical model that is based on the carbon model ROTH-C (Jenkinson and Rayner,  
1829 1977; Jenkinson et al. 1987; Coleman and Jenkinson, 1996) and the nitrogen-model SUNDIAL (Bradbury et al., 1993;  
1830 Smith et al., 1996). All major processes of the carbon and nitrogen dynamics are considered (Smith et al., 2010a,b).  
1831 Additionally, in ECOSSE processes of minor relevance for mineral arable soils are implemented as well (e.g., methane  
1832 emissions) to have a better representation of processes that are relevant for other soils (e.g., organic soils). ECOSSE  
1833 can run in different modes and for different time steps. The two main modes are site specific and limited data. In the  
1834 later version, basic assumptions/estimates for parameters can be provided by the model. This increases the uncertainty  
1835 but makes ECOSSE a universal tool that can be applied for large scale simulations even if the data availability is  
1836 limited. To increase the accuracy in the site-specific version of the model, detailed information about soil properties,  
1837 plant input, nutrient application and management can be added as available.

1838 During the decomposition process, material is exchanged between the SOM pools according to first order  
1839 rate equations, characterized by a specific rate constant for each pool, and modified according to rate modifiers  
1840 dependent on the temperature, moisture, crop cover and pH of the soil. The model includes five pools with one of  
1841 them being inert. The N content of the soil follows the decomposition of the SOM, with a stable C:N ratio defined for  
1842 each pool at a given pH, and N being either mineralized or immobilized to maintain that ratio. Nitrogen released from  
1843 decomposing SOM as ammonium (NH<sub>4</sub><sup>+</sup>) or added to the soil may be nitrified to nitrate (NO<sub>3</sub><sup>-</sup>).



1844 For spatial simulations the model is implemented in a spatial model platform. This allows to aggregate the  
1845 input parameter for the desired resolution. ECOSSE is a one-dimensional model and the model platform provides the  
1846 input data in a spatial distribution and aggregates the model outputs for further analysis. While climate data are  
1847 interpolated, soil data are represented by the dominant soil type or by the proportional representation of the different  
1848 soil types in the spatial simulation unit (this is in VERIFY a grid cell).  
1849 **Uncertainty:** In ECOSSE, uncertainty arises from three primary sources: parameters, forcing data (including spatial  
1850 and temporal resolution), and model structure. These uncertainties are not yet quantified.

1851

### 1852 *Bookkeeping models*

1853 We make use of data from two bookkeeping models: **BLUE** (Hansis et al., 2015) and **H&N** (Houghton &  
1854 Nassikas, 2017).

1855 The **BLUE** model provides a data-driven estimate of the net land use change fluxes. BLUE stands for  
1856 “bookkeeping of land use emissions”. Bookkeeping models (Hansis, 2015; Houghton, 1983) calculate land-use change  
1857 CO<sub>2</sub> emissions (sources and sinks) for transitions between various natural vegetation types and agricultural lands. The  
1858 bookkeeping approaches keep track of the carbon stored in vegetation, soils, and products before and after the land-  
1859 use change. In BLUE, land-use forcing is taken from the Land Use Harmonization, LUH2, for estimates within the  
1860 annual global carbon budget. The model provides data at annual time steps and 0.25 degree resolution. Temporal  
1861 evolution of carbon gain or loss, i.e., how fast carbon pools decay or regrow following a land-use change, is based on  
1862 response curves derived from literature. The response curves describe decay of vegetation and soil carbon, including  
1863 transfer to product pools of different lifetimes, as well as carbon uptake due to regrowth of vegetation and subsequent  
1864 refilling of soil carbon pools. In this report we present two versions of BLUE: BLUEvVERIFY and BLUEvGCP. The  
1865 BLUEvVERIFY version is a set of runs made for VERIFY, using the Hilda<sup>+27</sup> product (Ganzenmüller et al., 2022).

1866 The **H&N** model (Houghton et al., 1983) calculates land-use change CO<sub>2</sub> emissions and uptake fluxes for  
1867 transitions between various natural vegetation types and agricultural lands (croplands and pastures). The original  
1868 bookkeeping approach of Houghton (2003) keeps track of the carbon stored in vegetation and soils before and after  
1869 the land-use change. Carbon gain or loss is based on response curves derived from literature. The response curves  
1870 describe decay of vegetation and soil carbon, including transfer to product pools of different life-times, as well as  
1871 carbon uptake due to regrowth of vegetation and consequent re-filling of soil carbon pools. Natural vegetation can  
1872 generally be distinguished into primary and secondary land. For forests, a primary forest that is cleared can never  
1873 return back to its original carbon density. Instead, long- term degradation of primary forest is assumed and represented  
1874 by lowered standing vegetation and soil carbon stocks in the secondary forests. Apart from land use transitions  
1875 between different types of vegetation cover, forest management practices in the form of wood harvest volumes are  
1876 included. Different from dynamic global vegetation models, bookkeeping models ignore changes in environmental  
1877 conditions (climate, atmospheric CO<sub>2</sub>, nitrogen deposition and other environmental factors). Carbon densities at a  
1878 given point in time are only influenced by the land use history, but not by the preceding changes in the environmental

---

<sup>27</sup><https://landchangestories.org/hildaplus/>



1879 state. Carbon densities are taken from observations in the literature and thus reflect environmental conditions of the  
1880 last decades. In this study an updated H&N version submitted to the GCP2021 is used.

1881 **Uncertainty:** Uncertainties can be captured through simulations varying uncertain parameters, input data, or process  
1882 representation. A large contribution of uncertainty can be expected from various input datasets. Apparent uncertainties  
1883 arise from the land-use forcing data (Gasser et al., 2020; Hartung et al., 2021; Ganzenmüller et al., 2022), the  
1884 equilibrium carbon densities of soil and vegetation and allocation of material upon a land-use transition (Bastos et al.,  
1885 2021), and the response curves built to reflect carbon pool decay and regrowth after land-use transitions. Furthermore,  
1886 studies have shown that different accounting schemes (Hansis et al., 2015) and initialization settings at the start of the  
1887 simulations (Hartung et al., 2021) lead to different emission estimates even decades later.

1888

#### 1889 ***FAOSTAT***

1890 FAOSTAT: Statistics Division of the Food and Agricultural Organization of the United Nations provides  
1891 updates for the LULUCF CO<sub>2</sub> emissions for the period 1990-2019, available at:  
1892 <https://www.fao.org/faostat/en/#data/GT> and its sub-domains. The FAOSTAT emissions land use database is  
1893 computed following a Tier 1 approach of IPCC (2006). Geospatial data are the source of AD for the estimates of  
1894 emissions from cultivation of organic soils, biomass and peat fires. GHG emissions are provided by countries, regions  
1895 and special groups, with global coverage, relative to the period 1990-present (with annual updates). Land Use Total  
1896 contains all GHG emissions and removals produced in the different Land Use sub-domains, representing four IPCC  
1897 Land Use categories, of which three land use categories: forest land, cropland, grassland and biomass burning.  
1898 LULUCF emissions consist of CO<sub>2</sub> associated with land use and change, including management activities. CO<sub>2</sub>  
1899 emissions/removals are computed at Tier 3 using carbon stock change. To this end, FAOSTAT uses Forest area and  
1900 carbon stock data from FRA (2015), gap-filled and interpolated to generate annual time-series. As a result CO<sub>2</sub>  
1901 emissions/removals are computed for forest land and net forest conversion, representing respectively IPCC categories  
1902 “Forest land” and “Forest land converted to other land uses”. CO<sub>2</sub> emissions are provided as by country, regions and  
1903 special groups, with global coverage, relative to the period 1990-most recent available year (with annual updates),  
1904 expressed as net emissions/removals as Gg CO<sub>2</sub>, by underlying land use emission sub-domain and by aggregate (land  
1905 use total).

1906 **Uncertainty:** FAOSTAT uncertainties are not available.

1907

#### 1908 ***TRENDY DGVMs***

1909 The TRENDY (Trends in net land-atmosphere carbon exchange over the period 1980-2010) project  
1910 represents a consortium of dynamic global vegetation models (DGVMs) following identical simulation protocols to  
1911 investigate spatial trends in carbon fluxes across the globe over the past century. As DGVMs, the models require  
1912 climate, carbon dioxide, and land use change input data to produce results. In TRENDY, all three of these are  
1913 harmonized to make the results across the whole suite of models more comparable. In the case of VERIFY, 15 of the  
1914 16 models for TRENDY v10 (except for ISAM) were used. While describing the details of all the models used here



1915 is clearly not possible, DGVMs calculate prognostic variables (i.e., a multitude of C, H<sub>2</sub>O and energy fluxes) from the  
1916 following environmental drivers: air temperature, wind speed, solar radiation, air humidity, precipitation and  
1917 atmospheric CO<sub>2</sub> concentration. As the run progresses, vegetation grows on each pixel, divided into generic types  
1918 which depend on the model (e.g., broadleaf temperate forests, C3 crops), which cycle carbon between the soil, land  
1919 surface, and atmosphere, through such processes such as photosynthesis, litter fall, and decay. Limited human  
1920 activities are included depending on the model, typically removing aboveground biomass on an annual basis.

1921 Among other environmental indicators, DGVMs simulate positive and negative CO<sub>2</sub> emissions from plant  
1922 uptake, soil decomposition, and harvests across forests, grasslands, and croplands. Activity data is based on land use  
1923 and land cover maps and generally follows Approach 1 as described by the IPCC 2006 guidelines (enabling calculation  
1924 of only net changes from year to year). For TRENDY, pixel land cover/land use fractions were based on the land use  
1925 map LUH2 (Hurtt et al., 2020) and the HYDE land-use change data set (Klein Goldewijk et al., 2017a, b). Both of  
1926 these maps rely on FAO statistics on agricultural land area and national harvest data.

1927 **Uncertainty:** In TRENDY v10 uncertainties are model specific and described by Friedlingstein et al. (2022). The  
1928 spread of the 15 TRENDY models used by this study (Fig. 8) gives an idea of the uncertainty due to model structure  
1929 in dynamic global vegetation models, as the forcing data was harmonized for all models.

1930

### 1931 *Emissions from lateral transport of carbon (crops, wood, and inland waters)*

1932

1933 Production and consumption of carbon do not always occur on the same grid points. This is particularly relevant for  
1934 the land surface in the case of crops, wood products, and carbon transfers through the inland water network. The  
1935 purpose of the work here is primarily to convert the flux changes of the top-down inversions into NGHGI-like stock  
1936 changes. To convert the flux changes of the inversions (where a positive number represents a flux to the atmosphere,  
1937 i.e., a source) into NGHGI-like stock changes, one needs to add the crop sink and remove the crop source. The crop  
1938 sink comes from production numbers in the FAO food balance sheets, while the source is estimated by production  
1939 plus import minus export (all from the FAO food balance sheets), and both terms make use of conversion factors for  
1940 each commodity. We take the forestry balance sheets of FAO (production, import and export per commodity), and  
1941 convert to C mass. For a given year, the fraction of this mass that is released later in the atmosphere in each country  
1942 is modeled with an e-folding decrease driven by experimental data per country (Mason Earles et al., 2012). Lateral  
1943 transfers of carbon through inland waters also need to be removed from the inversion results as the terrestrial  
1944 biospheric CO<sub>2</sub> uptake leached into the inland water network represents a carbon sink, while the fraction that is  
1945 subsequently re-emitted as CO<sub>2</sub> before reaching the ocean is a carbon source. The inland water CO<sub>2</sub> outgassing  
1946 originates from carbon imported with runoff as dissolved CO<sub>2</sub> or produced in-situ from the decomposition of terrestrial  
1947 carbon inputs. Note further that a fraction of the net-uptake of atmospheric CO<sub>2</sub> over the continents does not  
1948 accumulate on land, but is instead exported through the inland water network to the oceans; this fraction is included  
1949 in the calculation. For regional carbon budgets, any river carbon export outside the boundaries of the region of interest  
1950 (in this case, EU27+UK) needs to be known to separate net uptake of atmospheric C from the actual land C sink.



1951 Carbon fluxes to the atmosphere from rivers and lakes were obtained from maps described in Zscheischler  
1952 et al. (2017). These methods are similar to those described previously in Petrescu et al. (2021b). The primary difference  
1953 is that the updated estimates include smaller lakes and reservoirs not represented in the Global Lakes and Wetland  
1954 Database through the use of a scaling law, in addition to the older results being created specifically for Europe, while  
1955 the newer results are part of a global product. The emissions from the previous work totaled 25.5 Tg C yr<sup>-1</sup> for the  
1956 EU27+UK, while those used here are 19.8 Tg C yr<sup>-1</sup> (with no variability from year-to-year). This difference is  
1957 therefore small compared to the river C export, which is included this year for the first time and averages -73.8 Tg for  
1958 the period 1990-2020.

1959 One important difference between the fluvial carbon exports reported here and those from a previous work  
1960 (Ciais et al., 2021) are that those reported here are rescaled to reasonable global flux reflecting bias in inter-  
1961 hemispheric exchange. Similar to Bastos et al. (2020), the dissolved organic carbon (DOC) and particulate organic  
1962 carbon (POC) exports were rescaled per basin to match the estimates of Resplandy et al. (2018). The global total  
1963 organic C was finally rescaled to 500 Tg C/yr, which is considered a reasonable global number based on different  
1964 reviews and synthesis efforts (Regnier et al., 2013).

1965  
1966

#### 1967 *Top-down CO<sub>2</sub> emissions estimates*

#### 1968 *CarboScope-Regional*

1969 **CarboScopeRegional (CSR)** (Munassar et al., 2022): CSR is a Bayesian Framework inversion system that employs  
1970 a-priori knowledge of the surface-atmosphere carbon fluxes to regularize the solution of the ill-posed inverse problem  
1971 arising from the sparseness of observations sampled over limited geographical locations throughout the domain of  
1972 interest. Due to the heterogeneity of biogenic fluxes, the convention in CSR is to optimize Net Ecosystem Exchange  
1973 (NEE) against measurements of CO<sub>2</sub> dry model fraction at 3-hourly temporal and 0.5° horizontal resolutions, while  
1974 ocean fluxes and anthropogenic emissions are prescribed given their better knowledge available compared with NEE.  
1975 The prior flux uncertainty is assumed to have a uniform shape in space and time and its spatial correlation is fitted to  
1976 a hyperbolic decay function following the assumption of Kountouris et al. (2018a, b). Model-data mismatch  
1977 uncertainty is defined weekly in the measurement covariance matrix varying over sites from 0.5 to 4 (ppm) according  
1978 to the ability for atmospheric transport models to sample the true concentration at such locations (Rödenbeck, 2005).  
1979 This uncertainty implicitly encompasses the combinations of atmospheric transport, representation, and measurement  
1980 errors and is assumed to be independent at different locations. To separate the lateral influences originating from  
1981 outside of the regional domain, the two-step scheme inversion (Rödenbeck et al., 2009) is applied to run a global  
1982 inversion with the Eulerian model TM3 at coarse resolutions to provide the lateral boundary conditions to the regional  
1983 inversion. In the regional inversion runs, the Lagrangian model STILT (Lin et al., 2003), forced by IFS data from  
1984 ECMWF, is used to calculate the surface sensitivities “footprints” over the regional site network (receptors) at hourly  
1985 temporal and 0.25° spatial resolutions. Typically, the prior fluxes of CO<sub>2</sub> are obtained from bottom-up model  
1986 estimations. Thus, the diagnostic biosphere model VPRM calculates the biogenic fluxes at hourly temporal resolution



1987 preserving the diurnal cycle. Ocean fluxes are obtained from the CarboScope ocean-based fluxes developed in-house  
1988 by Rödenbeck et al. (2014). Emissions of fossil fuel are taken from EDGAR\_v4.3 inventories updated every year  
1989 based on the British Petroleum statistics (BP), and are distributed in space and time using the COFFEE approach  
1990 (Steinbach et al., 2011) according to fuel-type and sector.

1991 The v2021 CSR inversions underwent updates in comparison with the previous v2019:

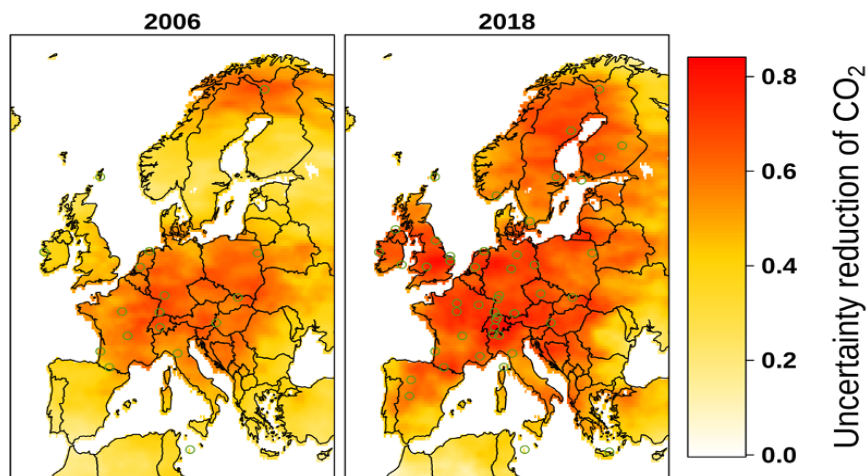
- 1992 • v2019 from Petrescu et al. (2021b) excluded observations from two sites: La Muela (LMU) in Spain because  
1993 of inconsistent datasets between releases, and Finokalia (FKL) in Greece due to errors in the dataset. These  
1994 exclusions resulted in a larger C sink from 2013 onwards (Fig. 9, upper plot). FKL observations start at this  
1995 time and are the dominant impact over south-east Europe, as it is the only site located there. In v2021  
1996 inversions, we included corrected datasets from the FKL site.
- 1997 • Two new flask sites were included in the v2021 inversions: Shetland Islands in the UK and Centro  
1998 Investigacion Baja in Spain. These sites are also used in the CarboScope global inversion that provides the  
1999 far-field contributions to the EU domain.

2000

2001 **Uncertainty:** Uncertainties from top-down (TD) estimates can be reported as posterior Bayesian uncertainties.  
2002 Following the methodology of Chevallier et al. (2007) the CSR inversion system computed maps of uncertainty  
2003 reductions for 2006 and 2018 (Fig. A4). The reduction is carried out through an ensemble of 40 members of inversions  
2004 using error realizations following a Monte Carlo (MC) approach. Circles on maps refer to locations of stations. In the  
2005 inversion system, a MC method is used to generate N ensembles of realizations of prior errors and model-data  
2006 mismatch errors. The inversion is repeated for each ensemble member starting from each set of prior and model-data  
2007 mismatch errors to generate posterior fluxes. The posterior uncertainty is calculated as the spread over the optimized  
2008 fluxes across the whole ensemble. The uncertainty reduction is then calculated as  $1 - (\sigma_{\text{post}} / \sigma_{\text{prior}})$ . It is clear that  
2009 larger ensembles will lead to better convergence of the error reduction. However, due to computational limitations, 40  
2010 ensemble members were selected as a good compromise.

2011





2012

2013 *Figure A4: CSR uncertainty reduction maps computed as  $1 - (\sigma_{\text{post}} / \sigma_{\text{prior}})$  for 2006 and 2018 using a Monte Carlo*  
2014 *approach focused on prior errors. The circles represent the observation stations network.*

2015 Figure A4 represents a preliminary attempt at how the inclusion of additional observation stations (additional  
2016 circles in the right-side figure for Germany, Switzerland, Finland compared to the left-side figure) might reduce the  
2017 uncertainty. However, the two different simulation years (2006 and 2018) might also differ in terms of other factors  
2018 which may lead to lower uncertainties in a given year (e.g., climatological conditions, such as the 2018 drought year).

2019 Several caveats remain. When comparing the uncertainty over pixels or subregions in the domain of interest,  
2020 the maps of uncertainty reduction should be interpreted together with the maps of posterior uncertainty to give a better  
2021 illustration of the magnitude of uncertainty. The maps of uncertainty reduction reflect only the random uncertainties.  
2022 The systematic uncertainties are still poorly characterized, including uncertainties due to atmospheric transport  
2023 modeling, dependence on the prior fluxes, and the weighting between the prior and observation uncertainties. To  
2024 improve knowledge of the systematic uncertainties, dedicated studies with controlled comparisons between inversions  
2025 using different atmospheric transport models (such as planned with the Community Inversion Framework, Berchet et  
2026 al., 2021) are still needed. Furthermore, the posterior uncertainty and uncertainty reductions between inversions  
2027 depend on internal parameterizations, e.g., the weighting of prior and observation uncertainties. Future efforts should  
2028 focus on establishing best practices on how to set-up inversions and quantification of systematic uncertainties,  
2029 including as well tests of the fidelity of models against data (Simmonds et al., 2021).

2030

2031

## 2032 **LUMIA**

2033 The LUMIA inversion system (Monteil and Scholze, 2021) is a regional atmospheric inversion system, which  
2034 was designed to produce estimates of the land-atmosphere carbon exchanges based on in-situ CO<sub>2</sub> observations from  
2035 the ICOS network. It relies on the FLEXPART 10.4 Lagrangian transport model (Pisso et al., 2019) to compute the  
2036 transport of CO<sub>2</sub> fluxes within a regional domain (15°W; 33°N to 35°E, 73°N) at a 0.5°, 3-hourly resolution. Boundary





2037 conditions are provided in the form of timeseries of far-field contributions at the observation sites, obtained from a  
2038 global TM5-4DVAR inversion (using the 2-step inversion approach of Rödenbeck et al., 2009). Both transport models  
2039 were driven by ECMWF ERA-Interim data, up to 2018, and by ECMWF ERA5 data afterwards.

2040 The inversions solve for weekly offsets to the prior NEE/NBP estimate, at a variable spatial resolution,  
2041 highest where the observational coverage is better (up to  $0.5^\circ$  upwind of the observation sites). The optimal solution  
2042 is searched for using a variational inversion approach (preconditioned conjugate gradient). The  
2043 inversions were constrained by in-situ and flask observations from 66 European  
2044 observation sites, although only a subset of these sites is usually available at a  
2045 given time. The observation uncertainties were set to 1 ppm/week at all sites (the  
2046 uncertainty of a single observation is therefore higher, on average 5.2 ppm, and given  
2047 by  $\sqrt{n}$ , with  $n$  the number of assimilated observations at the same site in a  $\pm 3.5$  day  
2048 window around the observation time). The prior NEE was produced using the LPJ-  
2049 GUESS model (Smith et al., 2014), driven by ECMWF ERA5 meteorological data.

2050 The inversion also accounts for (prescribed) anthropogenic  $\text{CO}_2$  fluxes from the EDGAR/TNO product  
2051 (<https://doi.org/10.18160/Y9QV-S113>) and for atmosphere-ocean  $\text{CO}_2$  exchanges from the Jena-CarboScope  
2052 oc\_v2021 product ([https://www.bgc-jena.mpg.de/CarboScope/oc/oc\\_v2021.html](https://www.bgc-jena.mpg.de/CarboScope/oc/oc_v2021.html)). The uncertainties on the prior NEE  
2053 were set proportional to the sum of the absolute value of the 3-hourly fluxes in each 7-day optimization interval (so  
2054 the uncertainty is not zero even if the net flux is zero), and scaled to a total value of 0.45 PgC/year, accounting for  
2055 covariances based on Gaussian (spatial) and exponential (temporal) correlation decay functions, with correlation  
2056 lengths of respectively 500 km and 1 month (see Monteil and Scholze, 2021, for details).

2057 The main differences from the LUMIA setup used in Thompson et al. (2014) are the specification of prior  
2058 and observation uncertainties (here made, on purpose, more comparable to those used in the CSR inversions), and the  
2059 implementation of flux optimization at a variable spatial resolution (which has negligible impact on the results but  
2060 improves the model performance).

## 2061 ***CIF-CHIMERE - land $\text{CO}_2$***

2062 CIF-CHIMERE is used for both  $\text{CO}_2$  land and  $\text{CO}_2$  fossil emission estimates, and this section only describes  
2063 the  $\text{CO}_2$  land estimates.

2064 The CIF-CHIMERE inversions have been generated with the variational mode of the Community Inversion  
2065 Framework (CIF, Berchet et al., 2021) coupled to the regional Eulerian atmospheric chemistry-transport model  
2066 CHIMERE (Menut et al., 2013; Mailler et al., 2017) and to its adjoint code. They are set-up in a manner that is close  
2067 to that of the PYVAR-CHIMERE inversions of Broquet et al. (2013), of Thompson et al. (2020) and of Monteil et al.  
2068 (2020).

2069 A European configuration of CHIMERE is used; this configuration covers latitudes  $31.75\text{-}73.25^\circ\text{N}$  and  
2070 longitudes  $15.25^\circ\text{W}$   $\text{-}34.75^\circ\text{E}$  with a  $0.5^\circ \times 0.5^\circ$  horizontal resolution and 17 vertical layers up to 200 hPa.



2071 Meteorological forcing for CHIMERE is generated using the European Center for Medium Range Weather  
2072 Forecasting (ECMWF) operational forecasts. Initial, lateral and top boundary conditions for CO<sub>2</sub> concentrations are  
2073 generated from the new CAMS global CO<sub>2</sub> inversions v20r2 (Chevallier et al., 2010).

2074 The inversion assimilates in situ CO<sub>2</sub> data from continuous measurements stations compiled in the VERIFY  
2075 Deliverable D3.12 and in the Table A1 from the VERIFY CIF Inversion Protocol (Thompson et al., 2021). More  
2076 specifically, the inversion assimilates 1-hour averages of the measured CO<sub>2</sub> mole fractions during the time window  
2077 12:00-18:00 UTC for low altitude stations (below 1000 masl) and 0:00-6:00 UTC for high altitude stations (above  
2078 1000 masl). The inversion optimizes 6-hourly mean NEE and ocean fluxes at the 0.5°×0.5° resolution of CHIMERE.  
2079 The anthropogenic CO<sub>2</sub> emissions, considered as perfect and consequently not optimized in the inversions, are based  
2080 on the spatial distribution of the EDGAR-v4.2 inventory, on national and annual budgets from the BP (British  
2081 Petroleum) Statistics and on temporal profiles at hourly resolution derived with the COFFEE approach (Steinbach et  
2082 al., 2011).

2083 The prior estimate of NEE and its uncertainty covariance matrix are specified using ORCHIDEE model  
2084 simulations of NEE and respiration, respectively, following the general approach of Broquet et al. (2011). The  
2085 temporal and spatial correlation scales for the prior uncertainty in NEE are set to ~1 month and 200 km (following the  
2086 diagnostics of Kountouris et al., 2015), with no correlation between the four 6-hour windows of the same day. The  
2087 ocean prior fluxes come from a hybrid product of the University of Bergen coastal ocean flux estimate and the  
2088 Rödenbeck global ocean estimate (Rodenbeck et al., 2014). Fluxes from biomass burning are ignored. The observation  
2089 error covariance matrix is set-up to be diagonal, ignoring the correlations between errors for different hourly averages  
2090 of the CO<sub>2</sub> measurements (which has been justified by the analysis of Broquet et al., 2011). The variances for hourly  
2091 data are based on the values from Broquet et al. (2013), which vary depending on the sites and season, and which are  
2092 derived from Radon model-data comparisons.

2093 About 12 iterations are needed to reduce the norm of the gradient of J by 95 %, using the MIQN3 limited  
2094 memory quasi-Newton minimisation algorithm (Gilbert et Lemaréchal, 1989). To cover the whole analysis period  
2095 (2005-2020), a series of 7-month (including an overlapping of 15 days between consecutive periods) inversions is  
2096 performed. Posterior estimates of NEE at 1-hourly and 0.5°×0.5° spatial resolution are generated for the full period of  
2097 analysis.

2098

2099 **Uncertainty:** Estimates of the uncertainty of regional inversions over Europe can be found by comparing against the  
2100 results of the other regional inversions in this work (the ensembles of EUROCOM, CarboScopeRegional, and  
2101 LUMIA).

2102

### 2103 ***GCP 2021***

2104 Top-down estimates of land biosphere fluxes are provided by a number of different inverse modeling systems  
2105 that use atmospheric concentration data as input, as well as prior information on fossil emissions, ocean fluxes, and  
2106 land biosphere fluxes. The land biosphere fluxes, and in some systems the ocean fluxes, are estimated using a statistical  
2107 optimization involving atmospheric transport models. The inversion systems differ in the transport models used,



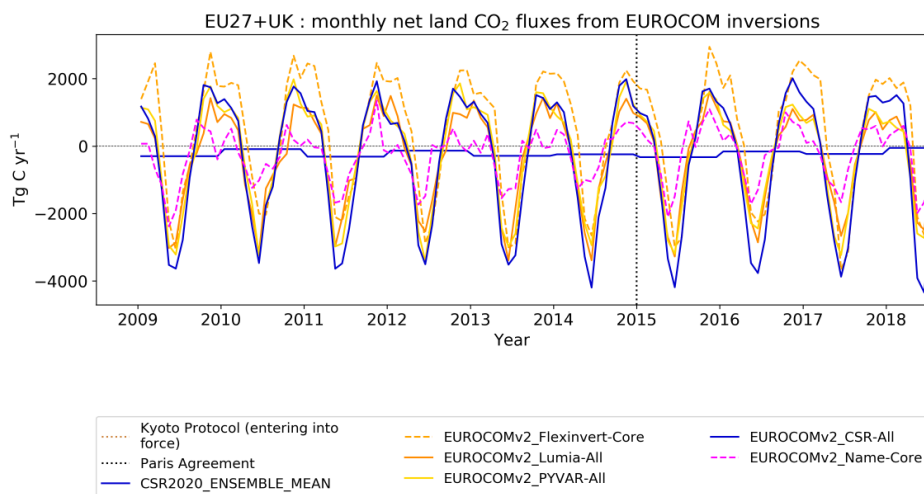
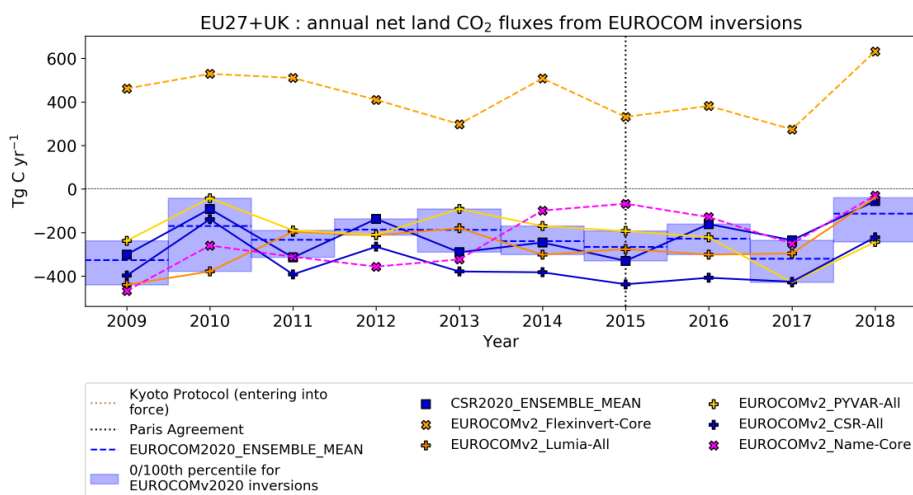
2108 optimization methods, spatiotemporal resolution, boundary conditions, and prior error structure (spatial and temporal  
2109 correlation scales), thus using ensembles of such systems is expected to result in more robust top-down estimates.

2110 For this study, the global inversion results are taken from all six of the models reported in the GCP 2021:  
2111 CTE (CarbonTracker Europe), CAMS (Copernicus Atmosphere Monitoring Service), CMS-Flux, JENA, NIES-  
2112 NIWA, and UoE, with spatial resolutions ranging from  $1^\circ \times 1^\circ$  for certain regions to  $4^\circ \times 5^\circ$ . For details see Friedlingstein  
2113 et al. (2022). Note that one of the ensemble members (CMS-Flux) only covers the period 2010-2020, and therefore  
2114 the ensemble results are only shown from 2010 until the last year common between all models (2018).

2115

### 2116 *EUROCOM*

2117 Top-down estimates at regional scales (up to  $0.25^\circ \times 0.25^\circ$  resolution) for the period 2009 – 2018 are taken  
2118 from three models used within EUROCOM (Monteil et al., 2020): LUMIA, PYVAR, and CSR. The NAME model  
2119 was excluded as visual inspection of monthly values identified it as a clear outlier. FLEXINVERT was excluded after  
2120 visual inspection of annual values identified it as a clear outlier (Fig. A5). These inversions make use of more than  
2121 30 atmospheric observing stations within Europe, including flask data and continuous observations. The CarboScope-  
2122 Regional (CSR) inversion system results were re-run for VERIFY using the extended period 2009-2020 using four  
2123 different settings: three network configurations using 15, 40, or 46 sites, and one using all 46 sites but a factor two  
2124 larger prior error correlation length scale (200 instead of 100 km). The CSR results reported to EUROCOM were not  
2125 used, being instead replaced by the mean of the four updated CSR runs.



2126

2127 *Figure A5: Annual (top) and monthly (bottom) timeseries for inversions in EUROCOM (Monteil et al., 2020).*  
 2128 *Inversions with solid lines were retained for the ensemble used in this work (shown in blue in the top figure for clarity).*  
 2129 *Note that the CSR values from EUROCOM have been replaced by the mean of four CSR simulations submitted under*  
 2130 *the VERIFY project (Appendix A). Negative fluxes represent a sink into the land surface.*

2131

2132

2133



2134

2135 ***Input data***

2136 ***CRUERA***

2137 The ERA5-Land (Muñoz-Sabater, 2019; 2021) dataset at 0.1-degree resolution over the global land surface  
2138 at hourly resolution was aggregated to three-hourly resolution and extracted for a 0.125 degree grid over Europe  
2139 (35N:73N, 25W:45E) to match the grid used in previous efforts within the VERIFY project. The variables extracted  
2140 are: air temperatures, wind components, surface pressure, downwelling longwave radiation, downwelling shortwave  
2141 radiation, snowfall, and total precipitation. From these, additional variables were calculated: total windspeed, specific  
2142 humidity, relative humidity, and rainfall. Of these, the air temperature, downwelling shortwave radiation, specific  
2143 humidity, and total precipitation were re-aligned with the CRU observation dataset (Harris et al., 2020) from 1901–  
2144 2020 so that monthly means at 0.5 degree pixels correspond exactly. Variation from observations is therefore present  
2145 only on sub-monthly temporal scales and sub-0.5 degree spatial scales. At the time of the model intercomparison,  
2146 ERA5-Land was only available from 1981-2020. Consequently, the years 1901-1980 were taken from the UERRA  
2147 HARMONIE-V1 dataset from ECMWF re-aligned with CRU observations under the VERIFY project and used in  
2148 Petrescu et al. (2021b). For both datasets, results were aggregated to daily and monthly temporal resolution for use  
2149 as needed in some models.

2150

2151 ***HILDA+***

2152 The full Hilda+ dataset is described in detail elsewhere (Winkler et al., 2020; Winkler et al., 2021). Hilda+  
2153 is available at 1x1km spatial and annual temporal resolution across the whole globe from 1960-2019 for six land use  
2154 classes (urban, cropland, pasture/rangeland, forest, unmanaged grass/shrubland, and sparse/no vegetation). The  
2155 algorithm uses earth observation data and land use statistics to generate annual land use/cover maps and transitions.  
2156 Probability maps for land use change categories are generated by using multiple earth-observation-based data  
2157 estimates of the extent of a given land cover category on a given pixel. The VERIFY project requires additional work  
2158 to satisfy the needs of the various modeling groups. For example, the maps were extended back to 1900 to meet the  
2159 needs of the DGVM groups. As observational data is lacking for the years pre-1960, the temporal trend of the  
2160 probability maps and the FAO land use database were used for extrapolation. In addition, forest areas were further  
2161 subdivided into six forest types (Evergreen, needle leaf; Evergreen, broad leaf; Deciduous, needle leaf; Deciduous,  
2162 broad leaf; Mixed; Unknown/Other) based on the ESA CCI land cover dataset (ESA 2017). Spatiotemporal forest type  
2163 dynamics within the forest category were included for 1992-2015. Before 1992 and after 2015, the static forest type  
2164 distribution as found in the years 1992 and 2015 in the ESA CCI land cover was assumed, respectively.

2165

2166 ***NITROGEN DEPOSITION***

2167 Wet and dry deposition maps of ammonium and nitrate covering Europe from 1995-2018 were calculated at  
2168 0.5 degree spatial and monthly temporal resolution by the EMEP MSC-W model (“EMEP model” hereafter). The  
2169 EMEP model is a 3-D Eulerian chemistry transport model (CTM) developed at the EMEP Centre MSC-W under the  
2170 Framework of the UN Convention on Long-Range Transboundary Air Pollution (CLRTAP). The EMEP model has



2171 traditionally been used to assess acidification, eutrophication and air quality over Europe, to underpin air quality policy  
2172 decisions (e.g., the Gothenburg Protocol), and has been under continuous development reflecting new scientific  
2173 knowledge and increasing computer power. The model was described in detail by Simpson et al. (2012) and later  
2174 updated as described in the annual EMEP status reports (Simpson et al., 2022, and references therein). For the  
2175 VERIFY project, output from the EMEP model version rv4.33 was used (Simpson et al., 2019), and averaged to annual  
2176 temporal resolution. In these simulations, the model was driven by meteorological data from the ECWMF IFS  
2177 (European Centre for Medium-Range Weather Forecasts – Integrated Forecast System) version cy40r1. Land-use data  
2178 were taken from the CORINE land-cover maps (de Smet and Hettelingh, 2001), the Stockholm Environment Institute  
2179 at York (SEIY), the Global Land Cover (GLC2000) database, and the Community Land Model (Oleson et al., 2010;  
2180 Lawrence et al., 2011). For more details see Simpson et al. (2017).

2181

#### 2182 ***COASTAL OCEAN FLUXES***

2183 Ocean CO<sub>2</sub> fluxes were prepared for use as prior estimates in the regional inversions by combining the Rödenbeck  
2184 global ocean estimate (Rödenbeck et al., 2014) with coastal ocean fluxes for Europe prepared under the VERIFY  
2185 project. The combined dataset was prepared by choosing the coastal flux map when available and otherwise the open  
2186 ocean map. The coastal ocean fluxes were generated for an area extending from the western Mediterranean to the  
2187 Barents Sea and cover shelf areas down to 500 m water depth or 100 km distance from shore. First, surface ocean  
2188 fCO<sub>2</sub> observations are taken from the annually updated SOCAT database (Bakker et al., 2016) and gridded to a  
2189 monthly 0.125°x0.125° grid. pCO<sub>2</sub> maps are created based on fitting a set of driver data (including sea surface  
2190 temperature, mixed layer depth, chlorophyll concentration, and ice concentration) against the gridded fCO<sub>2</sub>  
2191 observations. Both random forest and multi-linear regressions were used. The general procedure is described  
2192 elsewhere (Becker et al., 2021), but for the version reported here, random forest regressions were used instead of  
2193 multi-linear regression and the region was extended to the south. The dataset was divided into seven subregions  
2194 (Barents Sea, Norwegian Coast, North Sea, Baltic Sea, Northern Atlantic Coast/Celtic Sea, Southern Atlantic  
2195 coast/Bay of Biscay, western Mediterranean) and each region was fitted separately (leaf size: 20, bag size: 500). The  
2196 root mean square error (RMSE) of the random forest regressions was determined to be between 34 micro-atm (Baltic  
2197 Sea) and 10 micro-atm (Barents Sea). Random forest regressions consist of many regression trees, each based on a  
2198 random subset of data. Due to this internal structure, the overall RMSE can be seen as an out-of-box error estimate.  
2199 The final fluxes are calculated from the pCO<sub>2</sub> maps with the atmospheric xCO<sub>2</sub> in the marine boundary layer and six-  
2200 hourly wind speed data using the gas transfer coefficient and the Schmidt number after Wanninkhoff (2014), the  
2201 coefficient a<sub>q</sub> of 0.2814 calculated after Naegler (2009) and 6-hourly winds from the NCEP-DOE Reanalysis 2 product  
2202 (Kanamitsu et al., 2002).

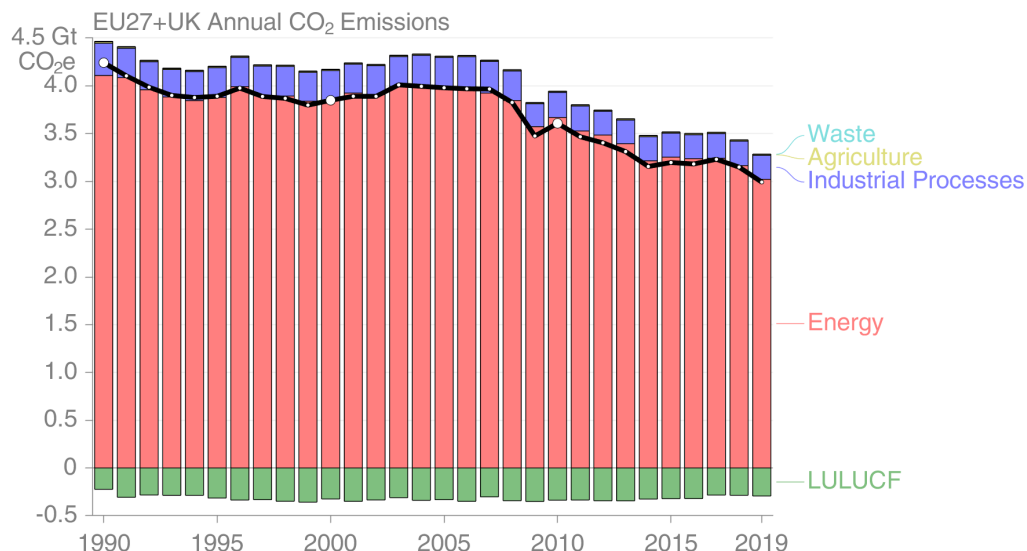
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2204



2205 **Appendix B**

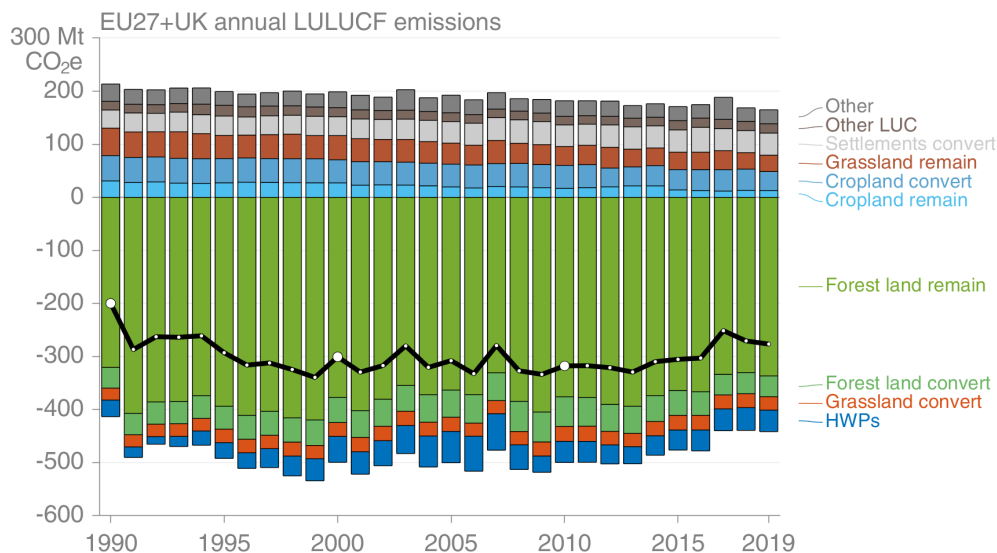
2206 **Overview figures**



2207

2208 *Figure B1: EU27+UK total annual GHG emissions from UNFCCC NGHGI (2021) submissions split per*  
 2209 *sector.*

2210



2211



2212 *Figure B2: EU27+UK total annual GHG emissions from the LULUCF sector split in categories and sub-categories,*  
 2213 *according to UNFCCC NGHGI (2021).*

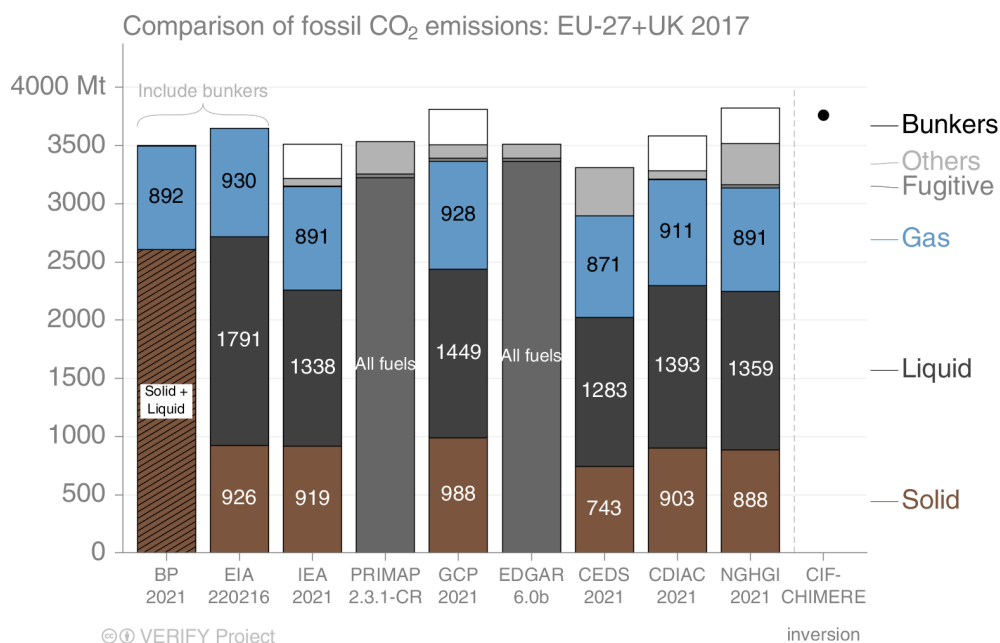
2214

2215 **CO<sub>2</sub> fossil breakdown by fuel type**

2216 Figure B3 shows the CO<sub>2</sub> fossil emission estimates from EU27+UK split by major source categories for each  
 2217 dataset for a single year. Sectors 1, 2, 3, and 5 are included for the UNFCCC NGHGI (2021) total, without indirect  
 2218 emissions. A breakdown of the nine other fossil BU data sources corresponding to UNFCCC NGHGI sectors or  
 2219 categories is not currently available.

2220 As in Andrew (2020), we observe good agreement for the EU27+UK between all BU data sources and the  
 2221 UNFCCC NGHGI (2021) data. The figure presents updated estimates for the year 2017, the most recent year when  
 2222 all datasets reported estimates. Sectors 1, 2, 3, and 5 are included for the UNFCCC NGHGI (2021) total, without  
 2223 indirect emissions.

2224 While most datasets agree well on total emissions, there are some differences. Both BP and the EIA include  
 2225 bunker fuels and exclude most industrial process emissions. CEDS appears to be underestimating emissions from solid  
 2226 fuels, for example lignite in Germany and oil shale in Estonia. IEA's emissions are lower because they exclude most  
 2227 industrial processes. GCP's total matches the NGHGI exactly by design but remaps some of the fossil fuels used in  
 2228 non-energy processes from "Others" to the fuel types used. CDIAC, PRIMAP, and EDGAR v6.0 all report total  
 2229 emissions very similar to the UNFCCC NGHGI (2021). Larger differences are seen in the disaggregation of fuel types,  
 2230 generally because of differing definitions.



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2232 *Figure B3: EU27+UK total CO<sub>2</sub> fossil emissions, as reported by nine bottom-up data sources: BP, EIA, CEDS, EDGAR v6.0, GCP, IEA,*  
 2233 *CDIAC, PRIMAPv2.3.1-CR and the UNFCCC NGHGI (2021) along with a top-down CIF-CHIMERE atmospheric inversion (black dot)*  
 2234 *(Fortems-Cheiney and Broquet, 2021). This figure presents the split per fuel type for year 2017. “Others” is other*  
 2235 *emissions in the UNFCCC’s IPPU, and international bunker fuels (the white boxes) are not usually included in total*  
 2236 *emissions at sub-global level. Neither EDGAR<sup>28</sup> (v6.0) nor PRIMAP publish a break-down by fuel type, so only the*  
 2237 *total is shown. For BP, the method description allows for emissions from natural gas to be calculated from BP’s*  
 2238 *energy data, but the data for solid and liquid fuels are insufficiently disaggregated to allow replication of BP’s*  
 2239 *emissions calculation method for those fuels.*

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2243 **Source specific methodologies: AD, EFs and uncertainties**

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2245 *Table B1: Source specific activity data (AD), emission factors (EF) and uncertainty methodology for all current*  
 2246 *VERIFY and non-VERIFY 2021 data products.*

<i>Data sources CO<sub>2</sub> emission calculation</i>	<i>AD/Tier</i>	<i>EFs/Tier</i>	<i>Uncertainty assessment method</i>	<i>Emission data availability method</i>
<b>UNFCCC NGHGI (2021)</b>	Country-specific information consistent with the IPCC Guidelines	IPCC guidelines / Country specific information for higher Tiers	IPCC guidelines ( <a href="https://www.ipcc-nggip.iges.or.jp/public/2006gl/">https://www.ipcc-nggip.iges.or.jp/public/2006gl/</a> ) for calculating the uncertainty of emissions based on the uncertainty of AD and EF, two different approaches: 1. Error propagation, 2. Monte Carlo Simulation  UBA Vienna provided yearly harmonized and gap-filled uncertainties	NGHGI official data (CRFs) are found at <a href="https://unfccc.int/ghg-inventories-annex-i-parties/2021">https://unfccc.int/ghg-inventories-annex-i-parties/2021</a> (last access: June 2022).

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**Fossil CO<sub>2</sub>**

<sup>28</sup>EDGAR v6.0 provides significant sectoral disaggregation of emissions, but not by fuel type due to license restrictions with the underlying energy data from the IEA.



<p><i>BP</i>  <i>CDIAC</i>  <i>EIA</i>  <i>IEA</i>  <i>GCP</i>  <i>CEDS</i>  <i>PRIMAP-Hist</i></p>	<p><i>For further details, see Andrew (2020)</i></p>			
<p><b>EDGAR v6.0</b></p>	<p>International Energy Agency (IEA) for fuel combustion                  Food and Agricultural Organisation (FAO) for agriculture                  US Geological Survey (USGS) for industrial processes (e.g., cement, lime, ammonia and ferroalloys production)                  GGFR/NOAA for gas flaring                  World Steel Association for iron and steel production                  International Fertilisers Association (IFA) for urea consumption and production                  Complete description of the data sources can be found in Janssens-Maenhout et al. (2019) and in Crippa et al. (2019)</p>	<p>IPCC (2006): Tier 1 or Tier 2 depending on the sector</p>	<p>Tier 1 with error propagation by fuel type for CO<sub>2</sub> and accounting for covariances.</p>	<p><a href="https://edgar.jrc.ec.europa.eu/dataset_ghg60">https://edgar.jrc.ec.europa.eu/dataset_ghg60</a></p>
<p><b>CIF-CHIMERE</b></p>	<p>Tier 3 top-down 0.1° x 0.1° resolution maps of annual averages of fossil CO<sub>2</sub> anthropogenic emissions from EDGAR v4.3.2                  Assimilation of satellite atmospheric concentration data: total column CO from IASI, and tropospheric column NO<sub>2</sub> from OMI</p>	<p>Tier 3 top-down regional inversions of CO and NO<sub>x</sub> emissions using EMEP/CEIP as prior knowledge of the emissions and CO<sub>2</sub>/CO and CO<sub>2</sub>/NO<sub>x</sub> emission ratios associated with the combustion of fossil fuel from EDGARv4.3.2.</p>	<p>Bayesian analysis in the CO and NO<sub>x</sub> inversions along with propagation of uncertainties in fCO<sub>2</sub>/CO and fCO<sub>2</sub>/NO<sub>x</sub> emission ratios</p>	<p>Detailed gridded data can be obtained by contacting the data providers:                  Gregoire Broquet  <a href="mailto:gregoire.broquet@lsce.ipsl.fr">gregoire.broquet@lsce.ipsl.fr</a></p>

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**CO<sub>2</sub> land: bottom-up**



<p><b>BLUEvGCP</b></p> <p><b>BLUEvVERIFY</b></p>	<p>From LUH2: data on wood harvest, land cover types (primary, secondary, pasture, crop), and gross land use transitions (e.g. from secondary to pasture and back); Based on Pongratz et al. (2008) and Ramankutty and Foley (1999): Plant functional types (PFTs) of natural vegetation types</p> <p>Same as above with land cover from HILDA+ (Ganzenmüller et al., 2022)</p>	<p>Tier 3 (IPCC, 2006); PFT and land-cover type specific response curves describing the decay and regrowth of vegetation and soil carbon</p>	<p>N/A</p>	<p>Detailed gridded data can be obtained by contacting the data provider:                  Julia Pongratz:  <a href="mailto:julia.pongratz@lmu.de">julia.pongratz@lmu.de</a></p>
<p><b>H&amp;N</b></p>	<p>Simple assumptions about C-stock densities (per biome or per biome/country) based on literature</p>	<p>Transient change in C-stocks following a given transition (time dependent EF after an land use transition)</p>	<p>N/A</p>	<p>Detailed gridded data can be obtained by contacting the data provider:                  Richard A. Houghton  <a href="mailto:rhoughton@woodwellclimate.org">rhoughton@woodwellclimate.org</a></p>
<p><b>ECOSSE</b></p>	<p>Tier 3 approach. The model is a point model, which provides spatial results by using spatial distributed input data (lateral fluxes are not considered). The model is a Tier 3 approach that is applied on grid map data, polygon organized input data or study sites.</p>	<p>IPCC (2006): Tier 3</p> <p>The simulation results will be allocated due to the available information (size of spatial unit, representation of considered land use, etc.).</p>	<p>N/A</p>	<p>Detailed gridded data can be obtained by contacting the data providers:                  Kuhnert, Matthias  <a href="mailto:matthias.kuhnert@abdn.ac.uk">matthias.kuhnert@abdn.ac.uk</a>                  Pete Smith:  <a href="mailto:pete.smith@abdn.ac.uk">pete.smith@abdn.ac.uk</a></p>
<p><b>EPIC-IIASA Croplands</b></p>	<p>Tier 3 approach. Cropland: static 1×1 km cropland mask from CORINE-PELCOM. Initial SOC stock from the Map of organic carbon content in the topsoil (Lugato et al., 2014). “Static” crop management and input intensity by NUTS2 calibrated for 1995-2010 (Balkovič et al., 2013). Crop harvested areas by NUTS2 from EUROSTAT. Parameterization of soil carbon routine was</p>	<p>IPCC (2006): Tier 3</p> <p>Land management and input factors for the cropland remaining cropland category as simulated by the EPIC-IIASA modeling platform, assuming the business-as-usual crop management calibrated for the 1995-2010</p>	<p>Sensitivity and uncertainty analysis of EPIC-IIASA regional soil carbon modeling (Balkovič et al, 2020).</p>	<p>Detailed gridded data can be obtained by contacting the data provider:                  Balkovič Juraj  <a href="mailto:balkovic@iiasa.ac.at">balkovic@iiasa.ac.at</a></p>



	updated based on Balkovič et al. (2020).	period. A 50-ha field is considered in each grid cell.		
<b>EPIC-IIASA grasslands</b>	Tier 3 approach. Grassland: static 1x1 km mask from CORINE & PELCOM 2000, including pastures, herbaceous vegetation, heterogeneous agricultural areas, and permanent cropland. Initial SOC stock from the map of organic carbon content in the topsoil (Lugato et al., 2014) with a spin-up. Static grassland management and input intensity as adopted from (Chang et al., 2016) and ISIMIP (Jägermeyr et al., 2021).	IPCC (2006): Tier 3 Land management and input factors for the grassland remaining grassland category as simulated by the EPIC-IIASA modeling platform, calibrated for the 1995–2020 period.	N/A	Detailed gridded data can be obtained by contacting the data provider: Juraj Balkovič: balkovic@iiasa.ac.at
<b>ORCHIDEE</b>	For the land cover/land use input maps: data on wood harvest from the FAO	Tier 3 model, process based. Any emission factors enter in the form of generic parameters for a given ecosystem type fit against observational data (both site-level and remotely sensed).	None, though some information on uncertainty due to model structure is given by looking at the spread from the TRENDY suite of models, of which ORCHIDEE is a member.	Detailed gridded data can be obtained by contacting the data providers: Matthew McGrath <a href="mailto:matthew.mcgrath@lsce.ipsl.fr">matthew.mcgrath@lsce.ipsl.fr</a> Philippe Peylin: <a href="mailto:peylin@lsce.ipsl.fr">peylin@lsce.ipsl.fr</a>
<b>CABLE-POP</b>	For the land cover/land use input maps: data on wood harvest and agricultural land from the FAO	Tier 3 model, process based. Any emission factors enter in the form of generic parameters for a given ecosystem type fit against	None, though some information on uncertainty due to model structure is given by looking at the spread from the TRENDY suite of models, of which CABLE-POP is a member.	Model output (gridded data) can be obtained by contacting the data provider: Jürgen Knauer: J.Knauer@westernsydney.edu.au

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		observational data (both site-level and remotely sensed).		
<b>TRENDY v10</b>	For the land cover/land use input maps: data on wood harvest and agricultural land from the FAO	Tier 3 models, process based. Any emission factors enter in the form of generic parameters for a given ecosystem type fit against observational data (both site-level and remotely sensed).	The spread of the 15 TRENDY models used gives an idea of the uncertainty due to model structure in dynamic global vegetation models, as the forcing data was harmonized for all models.	Detailed gridded data can be obtained by contacting the data provider: Sitch, Stephen S.A.Sitch@exeter.ac.uk
<b>Statistical prediction model for CO<sub>2</sub> in inland waters</b>	Hydrosheds 15s (Lehner et al., 2008) and Hydro1K (USGS, 2000) for river network, HYDROLAKES for lakes and reservoirs network and surface area (Messenger et al., 2016); river pCO <sub>2</sub> data from GloRiCh (Hartmann et al., 2014), lake pCO <sub>2</sub> database from Sobek et al. (2005); river channel slope and width calculated from GLOBE-DEM (GLOBE-Task-Team et al., 1999) and runoff data from Fekete et al. (2002). Geodata for predictors of pCO <sub>2</sub> and gas transfer coefficient include air temperature, precipitation and wind speed (Hijmans et al., 2005), population density (CIESIN and CIAT), catchment slope gradient (Hydrosheds 15s), and terrestrial NPP (Zhao et al., 2005)	N/A	Monte Carlo runs (uncertainty on pCO <sub>2</sub> and gas transfer velocity)	Detailed gridded data can be obtained by contacting the data providers: Ronny Lauerwald <a href="mailto:Ronny.Lauerwald@ulb.ac.be">Ronny.Lauerwald@ulb.ac.be</a> Pierre Regnier <a href="mailto:Pierre.Regnier@ulb.ac.be">Pierre.Regnier@ulb.ac.be</a>
<b>CBM</b>	National forest inventory data, Tier 2	EFs directly calculated by model, based on specific parameters (i.e., turnover and decay rates)	N/A used from IPCC	Detailed gridded data can be obtained by contacting the data providers: Giacomo Grassi <a href="mailto:Giacomo.GRASSI@ec.europa.eu">Giacomo.GRASSI@ec.europa.eu</a> Matteo Vizzarri <a href="mailto:Matteo.VIZZARRI@ec.europa.eu">Matteo.VIZZARRI@ec.europa.eu</a>



		defined by the user		Roberto Pilli <a href="mailto:roberto.pilli713@gmail.com">roberto.pilli713@gmail.com</a>
<b>EFISCEN-Space</b>	National forest inventory data, Tier 3	emission factor is calculated from net balance of growth minus harvest	Sensitivity analysis on EFISCEN V3 in the user manual (Schelhaas et al., 2007). Total sensitivity is caused by esp. young forest growth, width of volume classes, age of felling and few more. Scenario uncertainty comes on top of this when projecting in future.	Detailed gridded data can be obtained by contacting the data providers: Gert-Jan Nabuurs <a href="mailto:gert-jan.nabuurs@wur.nl">gert-jan.nabuurs@wur.nl</a> Mart-Jan Schelhaas <a href="mailto:martjan.schelhaas@wur.nl">martjan.schelhaas@wur.nl</a>
<b>FAOSTAT</b>	FAOSTAT Land Use Domain; Harmonized world soil; ESA CCI; MODIS 6 Burned area products	IPCC guidelines	IPCC (2006, Vol.4, p.10.33) - confidential Uncertainties in estimates of GHG emissions are due to uncertainties in emission factors and activity data. They may be related to, inter alia, natural variability, partitioning fractions, lack of spatial or temporal coverage, or spatial aggregation.	Agriculture total and subdomain specific GHG emissions are found for download at <a href="http://www.fao.org/faostat/en/#data/GT">http://www.fao.org/faostat/en/#data/GT</a> (last access: April 2022).
<b>CO<sub>2</sub> land: Top-down</b>				
<b>CSR</b> <b>GCP ensemble</b> (CTE, CAMS, CarboScope) <b>EUROCOM</b> (PYVAR-CHIMERE, LUMIA, FLEXINVERT, CSR, CTE-Europe) <b>LUMIA</b> <b>CIF-CHIMERE</b>	Tier 3 top-down approach, prior information from fossil emissions, ocean fluxes, and biosphere-atmosphere exchange Spatial resolutions ranging from 1°x1° for certain regions to 4°x5°. EUROCOM uses more than 30 atmospheric stations. CSR uses four different settings (as described in Appendix A2)	Tier 3 top-down Inversion systems based on atmospheric transport models	<b>CSR</b> - Gaussian probability distribution function, where the error covariance matrix includes errors in prior fluxes, observations and transport model representations. <b>GCP</b> : the different methodologies, the land-use and land-cover data set, and the different processes represented trigger the uncertainties between models. a semi-quantitative measure of uncertainty for annual and decadal emissions as best value judgment = at least a 68 % chance ( $\pm 1\sigma$ ) <b>EUROCOM</b> : account for source of uncertainties via prior and model and observation error covariance matrices; assessment of the resulting uncertainties in fluxes based on spread <b>LUMIA</b> : The prior uncertainties are constructed using standard	Detailed gridded data can be obtained by contacting the data providers:  <b>CSR</b> : Christoph Gerbig <a href="mailto:cgerbig@bgc-jena.mpg.de">cgerbig@bgc-jena.mpg.de</a> Saqr Munassar <a href="mailto:smunass@bgc-jena.mpg.de">smunass@bgc-jena.mpg.de</a>  <b>GCP</b> : Pierre Friedlingstein <a href="mailto:P.Friedlingstein@exeter.ac.uk">P.Friedlingstein@exeter.ac.uk</a>  <b>EUROCOM</b> : Marko Scholze <a href="mailto:marko.scholze@nateko.lu.se">marko.scholze@nateko.lu.se</a> Gregoire Broquet <a href="mailto:gregoire.broquet@lsce.ipsl.fr">gregoire.broquet@lsce.ipsl.fr</a>  <b>LUMIA</b> : Guillaume Monteil <a href="mailto:guillaume.monteil@nateko.lu.se">guillaume.monteil@nateko.lu.se</a>  <b>CIF-CHIMERE</b> : Gregoire Broquet <a href="mailto:gbroquet@lsce.ipsl.fr">gbroquet@lsce.ipsl.fr</a>



			deviations proportional to the sum of the absolute value of the hourly NEE aggregated in each weekly optimization interval (so, in essence, uncertainties are large when the daily cycle of NEE is large), spatial correlation lengths of 500 km (Gaussian) and temporal correlation lengths of 1 month (Exponential).	
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2253 *Table B2: Comparison of the processes included in the inventories, bottom-up models and inversions.*

Description	NGHGI	Global database	Process-based models				DGVMs				Bookkeeping Models			Inversions <sup>#</sup>
			E	E	C	E	C	T	O	B	B	H		
	U N F C C C <sup>a</sup>	F A O S T A T <sup>b</sup>	E C O S S E	E P I C - I I A S A	C B M	E F I S C E N - Space	C A B L E - P O P	T R E N D Y V I 0	O R C H I D E	B L U E v G C P	B L U E v V E R I F Y	H & N		
Forest total	E	E	N	N	E	E	E	Acc. table A1 in GCB 2021 (Friedlingstein et al., 2022)	E	E <sup>h</sup>	E <sup>h</sup>	E <sup>h</sup>		
Split FL-FL / FL-X / X-FL	E	E	N	N	E	E/N/N	E		E	E <sup>h</sup> /E/E	E <sup>h</sup> /E/E	E <sup>h</sup> /E/E		
Cropland total	E	N	E	E	N	N	I		E	E <sup>h</sup>	E <sup>h</sup>	E <sup>h</sup>		
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	N	



CO <sub>2</sub> fertilization	I	I	N	E	N	N	E	Acc. table A1 in GCB 2021 (Friedlingstein et al., 2022)	E	N <sup>i</sup>	N <sup>i</sup>	N <sup>i</sup>	
Climate induced impacts	I	I	N	E <sup>f</sup>	I <sup>b</sup>	I <sup>c</sup>	E		E	N <sup>i</sup>	N <sup>i</sup>	N <sup>i</sup>	
Natural disturbances (fires, insect, wind)	I	I	N	N	E	N	E		N	N <sup>i</sup>	N <sup>i</sup>	N <sup>i</sup>	
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	
Flux from Harvested Wood Products	E	N	N	N	I	N <sup>d</sup>	E	Acc. table A1 in GCB 2021 (Friedlingstein et al., 2022)	E	E	E	E	
Flux from Crop/Grass harvest	?	N	E	E <sup>e</sup>	N	N	E		E	I <sup>i</sup>	I <sup>i</sup>	I <sup>i</sup>	
Biomass burning	E	E	E	N <sup>g</sup>	E	N	N		N	E <sup>j</sup>	E <sup>j</sup>	E <sup>j</sup>	
N fertilization (with N dep)	I	N	E	N	N	N	E		N	N	N	N	
Flux from drained organic soils	I	E	E	N	I	N	N		I	E <sup>j</sup>	E <sup>j</sup>	E <sup>j</sup>	

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

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<sup>a</sup>UNFCCC and FAOSTAT are ensemble of country estimates calculated with specific methodology for each country, following some guidelines  
<sup>b</sup>The climate effects can be estimated indirectly by CBM, using external additional input provided by other models  
<sup>c</sup>EFISCEN Space: Increment is sensitive to weather, but average weather  
<sup>d</sup>EFISCEN has only production in m<sup>3</sup> but doesn't have a direct HWP module  
<sup>e</sup>Crop yield and residue harvest from cropland (20 % of residues harvested in case of cereals, no residue harvest for other crops)  
<sup>f</sup>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  
<sup>g</sup>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  
<sup>h</sup>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)  
<sup>i</sup>implicit by using observation-based carbon densities that reflect harvest/climate/natural disturbances  
<sup>j</sup>peat burning and peat drainage are not bookkeeping model output, but are added from various data sources during post processing  
<sup>k</sup>According Table 2 in Monteil et al. (2020) and Table A3 in Friedlingstein et al. (2019)





2270 #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  
2271 prior, and the posterior flux cannot really be disaggregated into contributions from separate processes. In a sense, as long as a process is  
2272 sufficiently significant to influence the CO<sub>2</sub> observations, it will have an impact on the inversion results  
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#### 2276 **Author contributions**

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2278 MJM processed original data, made Fig. 1,3-10, A2, A3, A5, and edited the final manuscript; AMRP designed the  
2279 initial research, led the discussions, wrote the initial draft of the paper and helped edit all the following versions; RMA  
2280 made Fig. 2, A1, B3; BM provided the new UNFCCC gap-filled uncertainties and provided extensive support on  
2281 questions related to NGHGs; PP, VB, and MJM processed the original data submitted to the VERIFY portal; PP, PB,  
2282 and MJM designed and are managing the web portal; GP provided Fig. B1 and B2; GP, RMA, FD, BM, and GG made  
2283 detailed reviews; CQ made Fig. 11; SM made Fig. A4; PC, GB, PIP, MJ, RL, MK, JK, FC, OT, JP, RG, FNT, JB and  
2284 GG gave detailed comments and advice on previous versions of the manuscript; all remaining co-authors provided  
2285 data and commented on specific parts of the text related to their data sets.

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#### 2287 **Competing interests**

2288 The authors declare that they have no conflict of interest.

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