

# Differences in anthropogenic greenhouse gas emissions estimates explained

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## Abstract

We examine differences in global and national greenhouse gas (GHG) emissions estimates, focusing on the role of varying system boundaries and conceptual approaches in driving these variations. Despite consensus among assessments and datasets that GHG emissions continue to increase and that trends are far from aligned with the Paris Agreement goals, estimates can differ significantly. Our review finds three main reasons for these differences. First, datasets vary in their coverage of gases, sectors and countries; second, there are different approaches to defining ‘anthropogenic’ emissions and removals in the land use, land-use change and forestry (LULUCF) sector; and third, the Paris Agreement doesn’t cover all relevant sources of emissions, including the cement carbonation sink and ozone depleting substances. As different assessments have different objectives, they may deal with these issues differently. We highlight three assessment conventions that report or use emissions data: those focused on interpreting national progress, policies and pledges under the Paris Agreement; those consistent with integrated assessment modelling (IAM) benchmarks of emissions under different warming scenarios; and those consistent with climate forcing assessments. Considering annual average emissions over the period 2014 to 2023, we show global totals of 44.4 GtCO<sub>2</sub>e yr<sup>-1</sup> [90% CI ± 4.9], 54.5 GtCO<sub>2</sub>e yr<sup>-1</sup> [90% CI ± 5.6], and 56.4 GtCO<sub>2</sub>e yr<sup>-1</sup> [90% CI ± 5.7] for these three conventions, respectively. We suggest that users of GHG emissions data increase transparency in their decision criteria for choosing datasets and setting the scope of an assessment. The data used in this study to make figures 9-14 is available at: <https://doi.org/10.5281/zenodo.15126539> (Lamb, 2026).

## 44 **1 Introduction**

45 A key indicator to assess human influence on the climate is total anthropogenic greenhouse gas (GHG) emissions. At a global  
46 level, tracking developments in this metric is necessary to evaluate progress towards the climate objectives of the Paris  
47 Agreement - including the human contribution to warming so far, the timing of peak emissions, and how fast emission reductions  
48 need to proceed in the coming decades. At the national level, tracking GHG emissions trends is instrumental to evaluating the  
49 climate policy implementation and progress.

50  
51 Despite its centrality to climate and climate policy assessments, different communities report different levels and trends in total  
52 anthropogenic GHG emissions - even though all assessments show that GHG emissions have conclusively increased over the  
53 past decades, and are off track from a pathway consistent with the goals of the Paris Agreement (Forster et al., 2024; IPCC,  
54 2022; UNEP, 2024; UNFCCC, 2022c). Nevertheless, as we will show below, global estimates of annual GHG emissions can  
55 vary by a margin of several GtCO<sub>2e</sub>. This is a phenomenon that has received increasing attention in the literature and in global  
56 assessments under the Intergovernmental Panel on Climate Change (IPCC) (Gidden et al., 2023; Grassi et al., 2023; IPCC,  
57 2024). These differences are often related to different input datasets, different definitions and scope, as well as decisions  
58 regarding what is included in the estimates (Andrew, 2020), in addition to the underlying parametric uncertainties.

59  
60 It is important to distinguish differences in emissions reporting that result from different methodologies and data sources, which  
61 can represent uncertainty and data quality in our understanding, versus those that result from alternative conceptual approaches  
62 and system boundaries. An example of the former would be the use of different emissions factors (EFs) across datasets or data  
63 versions, which provide an estimate of the emissions associated with a given activity. An example of the latter is the fact that  
64 assessments may choose to exclude certain emissions categories, for instance those from biomass fires, while others include  
65 them. In some cases, it may not be made explicit that an emission source is excluded in an assessment. In this article we are  
66 concerned with the latter kind of decisions and the fact that specific *system boundary choices* greatly matter for tracking GHG  
67 emissions.

68  
69 There is no single agreed approach to setting the system boundaries of an anthropogenic GHG emissions assessment. Even if the  
70 same input data and emission factors are used, different communities have developed their own conventions on which categories  
71 of emissions are included in an assessment. Two of the main communities include users of national greenhouse gas inventories  
72 (used for country reporting), and the scientific communities performing mitigation analysis, integrated assessment modeling  
73 (IAM), and climate modelling. Further, national, regional and global anthropogenic GHG emissions are widely depicted in a  
74 variety of reports and the decision criteria for which components of emissions they include or exclude are often not transparent  
75 (Boehm et al., 2023; European Commission, 2024; Forster et al., 2024; UNEP, 2024; UNEP and CCAC, 2021; USGCRP, 2023).

76  
77 It is critical to explain the decision criteria behind system boundary choices in emissions reporting, and to understand the  
78 consequences of these differences. Besides the fact that different published estimates lead to general confusion among non-  
79 domain experts, this issue can compromise important science-policy processes. For example, differences in land use, land-use  
80 change and forestry (LULUCF) emissions between national inventories and IAMs are highly consequential for calculating  
81 benchmarks to meet the 1.5°C and 2°C goals, including when countries should reach net-zero, or for calculating whether net-zero  
82 targets are sufficient to stabilise global temperatures (Allen et al., 2025; Gidden et al., 2023; Grassi et al., 2021). Further, there is  
83 a risk that observers start to lose trust in emissions estimates, including the official inventories published by countries, simply  
84 because they are perceived to misrepresent or exclude certain sources (Mooney et al., 2021; Yona, 2025).

85  
86 In this perspective we ask three questions. First, what are the main system boundary issues causing anthropogenic GHG  
87 estimates to differ? Second, what conventions are taken in different assessment communities with respect to these system  
88 boundaries? And third, what is the possible spread in global or national GHG estimates according to these conventions? In  
89 answering these questions, we aim to explain and promote transparency in key decision criteria that lie behind GHG emissions  
90 assessments.

91  
92 In terms of scope, our discussion covers the main well-mixed anthropogenic GHGs that are covered by the Kyoto Protocol, the  
93 Paris Agreement and the Montreal Protocol, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and  
94 Fluorinated gases (F-gases) as well as Ozone Depleting Substances (ODS). We do not extend our analysis to other climate  
95 relevant emissions (e.g. SO<sub>x</sub>, NO<sub>x</sub>, CO, etc.), while recognizing that these too have relevant impacts on atmospheric chemistry

96 and the climate. We also do not consider the role of global warming potential metrics, even though different choices here can  
97 obviously lead to varying estimates. We consider differences in emissions estimates primarily at the national or global level,  
98 rather than subnational levels such as gridded data or urban emissions estimates - while noting that gridded data is often needed  
99 for emission validation exercises, with spatial data also relevant in the context of wildfires and other LULUCF components.  
100 Finally, while our discussion covers anthropogenic emissions from terrestrial sources (i.e. on land), it excludes fluxes taking  
101 place on the open ocean (apart from those related to shipping) as these are generally not included in national GHG inventories or  
102 other accounts of anthropogenic emissions.

## 103 **2 Three reasons why greenhouse gas estimates can differ**

104 Emissions inventories form the basis for most national and global reporting of anthropogenic GHG emissions. These ‘bottom-up’  
105 accounts are constructed by tracking human activities in different domains (e.g., fuel use, cement production, land use  
106 transitions, livestock numbers) and estimating the expected GHG emissions or removals under different conditions (e.g.  
107 technology or climate). Combustion emissions are usually estimated by multiplying fuel use by a corresponding emission factor.  
108 Some of these accounts also depend on modelling, particularly for agricultural and land-based activities. A number of different  
109 datasets are now available and are in widespread use across the climate research community to estimate global and national GHG  
110 emissions. However, despite being well documented, there are several key reasons why studies using them can arrive at quite  
111 different estimates of global or national emissions.

### 112 **2.1 Datasets vary in their coverage of gases, sectors and countries**

113 Bottom-up datasets generally aim to cover the set of emissions sources outlined by the United Nations Framework Convention  
114 on Climate Change (UNFCCC, 2018b). In terms of gases, this includes CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and a subset of F-gases covering  
115 hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Nitrogen Trifluoride (NF<sub>3</sub>) and Sulfur Hexafluoride (SF<sub>6</sub>). These are often  
116 referred to in the literature as the “Kyoto gases” since they were covered under the Kyoto Protocol. In terms of sectors, national  
117 reporting to the UNFCCC includes five main categories (and many more subcategories) which sum to the total: 1. Energy, 2.  
118 Industrial process and product use (IPPU), 3. Agriculture, 4. LULUCF, and 5. Waste. Parties to the UNFCCC report their  
119 emissions according to this scope of gases and sectors, and do so using the methods, formats and conventions laid out in the  
120 IPCC Guidelines on National Greenhouse Gas Inventories (IPCC, 2006, 2019) (hereafter referred to as the “IPCC Guidelines”).  
121 Independent inventories outside of the UNFCCC process use similar methods, but often using simplified or harmonised  
122 assumptions across countries to ensure consistency and comparability.

123  
124 The IPCC Guidelines define emissions and removals as “taking place within national territory and offshore areas over which the  
125 country has jurisdiction”. This means that emissions and removals are allocated to where they occur, though, there are exceptions  
126 discussed below. Many countries also have jurisdiction over some ocean areas (e.g., Exclusive Economic Zones, EEZ), and if  
127 these emissions and removals are anthropogenic, then they are in principle included. Anthropogenic emissions and removals in  
128 areas that are not allocated to a country, primarily international aviation and shipping, are reported as a memo called ‘bunkers’,  
129 and not included in country totals in most inventories, though exceptions exist.

130  
131 The national GHG inventories that parties submit to the UNFCCC cannot currently be used to make a complete assessment of  
132 global emissions. While they do, in principle, cover all “Kyoto gases” and all sectors, reporting tends to be sporadic for all but  
133 Annex I (essentially developed) countries. Parties are guided to submit an annual time series starting in 1990, reporting  
134 emissions up to two years prior, which would cover many use cases (UNFCCC, 2018b). However, in practice the UNFCCC  
135 recognises that parties have different capabilities and statistical infrastructures, and has made a series of allowances for non-  
136 Annex I parties: they have the flexibility to report three gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) instead of all seven (i.e. they may exclude F-  
137 gases); they may report annual time series from 2020 onwards instead of from 1990; and they may do so up to three years prior  
138 instead of two (UNFCCC, 2018b §48, §57 & §58). The Biennial Transparency Reports have improved the frequency of  
139 inventory reporting, but still make allowances for Least Developed Countries and Small Island Developing States to submit at  
140 their discretion. As a result, national GHG inventories are typically only complete and timely for Annex I countries from 1990  
141 onwards, covering about one-third of total world emissions.

142  
143 Consequently, third-party datasets produced by researchers and international institutes are frequently used to report global or  
144 national totals, including trends before 1990. These third-party datasets usually explicitly follow the inventory conventions for

145 sectors and coverage of gases, but make use of national statistics for activity data and independently assessed emissions factors,  
146 often based on general default values (also known as “Tier 1” estimates). Key global datasets that cover multiple sectors and  
147 gases with a global scope include: the Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2024;  
148 Janssens-Maenhout et al., 2019); the Community Earth atmospheric Data System (CEDS) (Hoesly et al., 2025); and the  
149 PRIMAP-hist national historical emissions time series (PRIMAP-Hist) (Gütschow et al., 2025). Some data sets focus on specific  
150 GHGs or sectors, including the Global Carbon Project’s (GCP’s) Global Carbon Budget (GCB) (Friedlingstein et al., 2025b),  
151 Global Methane Budget (Saunio et al., 2025) and Global Nitrous Oxide Budget (GNB) (Tian et al., 2024); the Energy Institute’s  
152 Statistical Review of World Energy (EI - formerly published by BP) (Energy Institute, 2025); the International Energy Agency  
153 (IEA) GHG Emissions from Energy dataset (IEA, 2024), and the Food and Agriculture Organisation of the UN (FAOSTAT)  
154 Greenhouse Gas Emissions dataset (FAO, 2025b).

155  
156 Several further useful datasets include the gap-filled and harmonised dataset of LULUCF data based on National GHG  
157 inventories (JRC-NGHGI) (Melo et al., 2025); the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)  
158 dataset of methane emissions (Höglund-Isaksson et al., 2020); the Global Fire Emissions Database (GFED), the Global Fire  
159 Assimilation System (GFAS), and the Global Wildfire Information System (GWIS) for fire emissions (Giglio et al., 2013;  
160 GWIS, 2025; Kaiser et al., 2012; van der Werf et al., 2017); Andrew (2025) for cement-process emissions; and inversion datasets  
161 for ODS and F-gas emissions (Forster et al., 2024; Velders et al., 2015; WMO, 2022).

162  
163 Third-party datasets are useful to track global, national, and sectoral trends, over long-time periods, and provide independent  
164 checks against official NGHGI reporting to the UNFCCC. However, their appropriate use is complicated by several issues. The  
165 first is that, as it stands, no single third-party dataset has complete and up-to-date coverage of all UNFCCC relevant gases,  
166 sectors and countries (Table 1). Only two datasets cover all GHGs in the convention (EDGAR and PRIMAP-Hist) and while  
167 many cover agriculture, most exclude LULUCF emissions, though EDGAR now includes JRC-NGHGI. Only two datasets cover  
168 global emissions of non-CO<sub>2</sub> LULUCF emissions (FAOSTAT, PRIMAP-Hist). To obtain a complete global or national total  
169 across all gases it is therefore often necessary to combine multiple datasets.

170  
171 Second, due to different formats, overlaps between datasets, and varying methodological approaches, it is generally advised to  
172 take care when combining them. Each dataset is not necessarily like-for-like; EDGAR for example often applies global average  
173 emission factors (Tier 1) while most UNFCCC Annex I countries apply national emission factors and/or models (Tier 2 or 3),  
174 which can lead to differences in emission levels and trends, particularly at the national level and for non-CO<sub>2</sub> GHGs. Further,  
175 individual datasets have different approaches to dealing with certain sectors. For instance, in the case of emissions from bunker  
176 fuels (international aviation and shipping): the national GHG inventories report these as a memo item for each country (i.e.,  
177 excluded from national totals); CEDS, IEA, EDGAR and GCB report these as a single stand-alone quantity which can be  
178 interpreted as a memo, but is often allocated to global totals; EI includes these in national totals; and PRIMAP-Hist excludes  
179 them entirely. Differences in accounting for emissions and removals in the LULUCF sector are even more consequential, as  
180 discussed in the next section.

181  
182 Third, there can be significant dependencies between datasets (Andrew, 2020). Even though many datasets rely ultimately on  
183 activity data reported by the IEA, the UN Statistics Division (UNSD), EI and FAOSTAT, these data can have different levels of  
184 details and can be applied differently (for example, in a sector or reference approach, Tier 1 or Tier 3, etc). For example, the  
185 PRIMAP-Hist dataset is an amalgamation of several underlying data products, with two individual time series: the “CR  
186 scenario”, which prioritises national GHG inventory data and gap fills these with third-party data (EI, Andrew, FAO, EDGAR);  
187 and the “TP scenario”, which prioritises the latter third-party data. Conversely, the FAOSTAT GHG emissions dataset has begun  
188 to incorporate UNSD and PRIMAP-Hist data for energy, IPPU and waste emissions. Changes in underlying datasets can  
189 therefore cascade across many of the datasets we discuss here.

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Dataset	Reference	Gases	Sector coverage							Reporting frequency and delay
			1.A. Energy (fuel combustion)	1.B. Energy (fugitive emissions)	1.D.1. Energy (Intl. Bunkers) <sup>†</sup>	2. Industrial process and product use	3. Agriculture	4. Land use, land use change and forestry	5. Waste	
UNFCCC Inventories*	UNFCCC (2025)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases	yes	yes	yes	yes	yes	yes <sup>‡</sup>	yes	Annual, 2 year delay (Annex 1)
EDGAR	Crippa et al. (2024)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases	yes	yes	yes	yes	yes	yes <sup>‡</sup>	yes	Annual, 1 year delay
IEA	IEA (2024)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O	yes	yes	yes	some fluxes	no	no	no	Annual, 1 year delay
CEDS	Hoesly et al. (2025)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O	yes	yes	yes	yes	yes	no	yes	Annual, 1 year delay
GCB	Friedlingstein et al. (2025b)	CO <sub>2</sub>	yes	yes	yes	most fluxes <sup>¶</sup>	most fluxes <sup>¶</sup>	yes <sup>‡</sup>	yes	Annual, 1 year delay
EI (BP)	Energy Institute (2025)	CO <sub>2</sub> , CH <sub>4</sub>	yes	yes	yes <sup>§</sup>	some fluxes <sup>#</sup>	no	no	some fluxes	Annual, 1 year delay
PRIMAP-Hist	Gütschow et al. (2025)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases	yes	yes	no	yes	yes	yes <sup>‡</sup>	yes	Annual, 1 year delay
FAOSTAT	FAO (2025b)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases	some fluxes <sup>**</sup>	some fluxes <sup>**</sup>	some fluxes <sup>**</sup>	some fluxes <sup>**</sup>	yes	yes <sup>‡</sup>	some fluxes <sup>**</sup>	Annual, 2 year delay <sup>††</sup>

**Table 1: Bottom-up emissions datasets of anthropogenic GHG emissions and their characteristics.** Several subcategories of the energy sector are shown to highlight their exclusion in some datasets. Datasets are named and referenced in section 2.1. Notes: \* Only Annex I countries reliably submit complete inventories each year. <sup>†</sup> Bunkers are included as a memo item in UNFCCC inventories (excluded from national totals), and typically as a separate “country” in other datasets. <sup>‡</sup> Definitions of LULUCF differ, as discussed in section 2.2. <sup>¶</sup> For some countries, excludes lime, glass and other decomposition in sector 2, and liming in sector 3. <sup>§</sup> Included in national totals and not reported separately. <sup>#</sup> Includes cement only. <sup>\*\*</sup> FAO includes agrifood system emissions across all sectors, and separately a version of the PRIMAP-Hist database for non-agrifood sectors. <sup>††</sup> Currently FAOSTAT is at T-0 for forest emissions and regularly at T-1 for peatland drainage and fire emissions. Adapted from (Andrew, 2020). Note that PRIMAP-Hist includes two datasets (Hist-CR and Hist-TP), which prioritise data from national inventories and third-party sources, respectively.

A further complication is that dataset methodologies can carry implicit system boundary decisions. For instance, the IPCC Guidelines on National Greenhouse Gas Inventories (IPCC, 2006, 2019) take a territorial approach, but recommend at Tier 1 the use of fuel sales data to calculate road transport emissions. Since fuel use is transboundary in nature, this means that large discrepancies can be observed between the Tier 1 inventory approach and higher Tier datasets that apply a more refined territorial principle (i.e. using modelling studies to estimate fuel consumption within a country) (e.g. BMK, 2023). Likewise, the IPCC Tier 1 methodology for Harvested Wood Products (HWPs) follows the so-called production approach and explicitly assumes that end-of-life emissions from traded HWPs occur within the country from which they were exported, rather than in the importing country (IPCC, 2019). Assuming all countries follow the same principle, then these differences will balance out at the global level, but can lead to significant inconsistencies between and within datasets for countries that have large trade flows in biomass products in particular.

Together, these issues mean that dataset choices matter, and that assessments often have to combine different datasets to gain totals that are comparable to the scope of national GHG inventories. Further, this requires caution due to potential overlaps and conceptual differences between datasets.

## 222 **2.2 There are different approaches to defining ‘anthropogenic’ emissions**

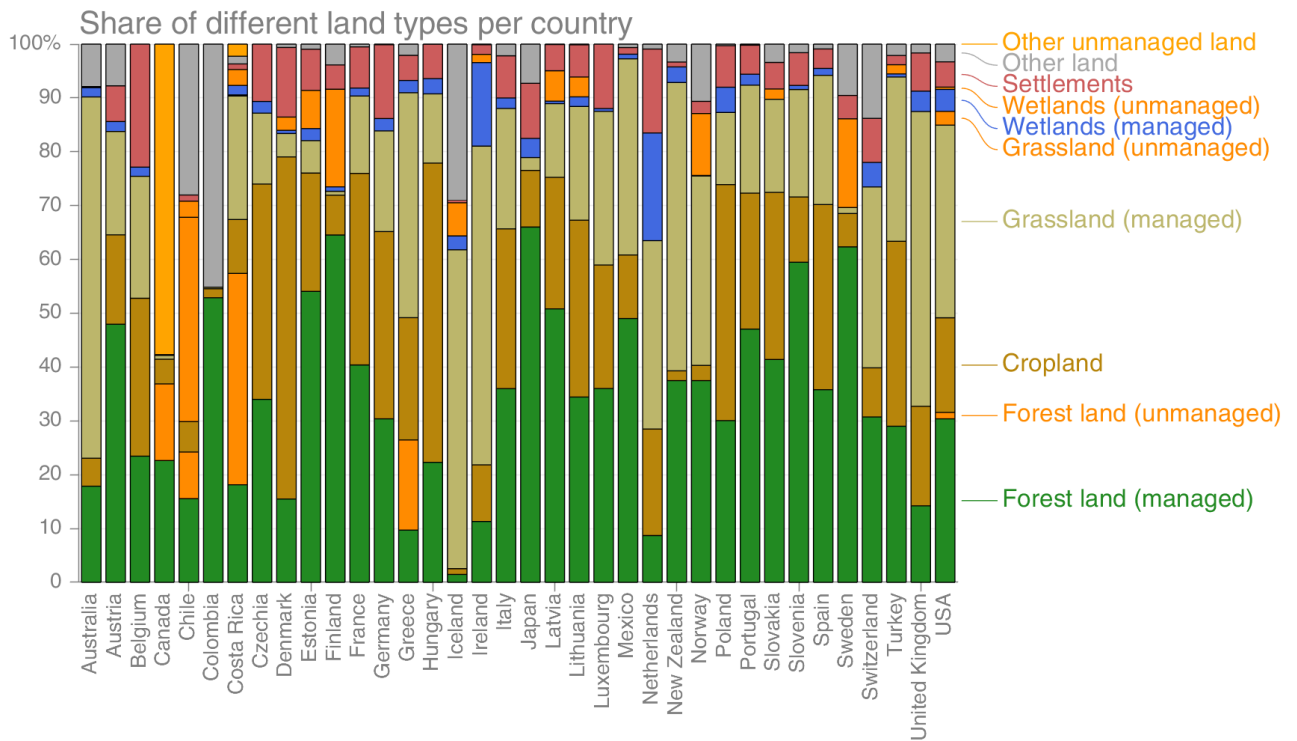
223 A second issue affecting comparability in emissions assessments is that different communities and datasets have different  
224 approaches to estimating or even defining ‘anthropogenic’ emissions and removals (together: fluxes). Specifically, this issue  
225 arises in connection with GHG fluxes in terrestrial ecosystems (e.g. forests and wetlands), where a given area of land can be  
226 influenced by three main types of effects: (1) direct anthropogenic effects, such as changes in land use (e.g. deforestation or crop  
227 abandonment) and various types of management practices; (2) indirect anthropogenic effects, which include environmental  
228 changes caused by humans, like alterations in temperature, precipitation, CO<sub>2</sub> levels, and nitrogen deposition which can impact  
229 growth rates, mortality, decomposition, and natural disturbance patterns; and (3) natural effects, including climate variability and  
230 inherent natural disturbances such as fires and pests (Grassi et al., 2018; IPCC, 2019). The definitional difficulties arise with the  
231 second category of ‘indirect anthropogenic’ effects, such as when increased atmospheric CO<sub>2</sub> concentrations (resulting from  
232 anthropogenic emissions) influence forest growth and lead to increased removals.  
233

234 The separation of direct anthropogenic, indirect anthropogenic, and natural sources of emissions is conceptually challenging and  
235 can be difficult to communicate to users of emissions data. Here we cover three of the main areas of emissions accounting where  
236 indirect anthropogenic effects arise, all of which occur in the LULUCF sector of national inventories, but also to some degree in  
237 the agriculture sector.

### 238 **2.2.1 Forest land CO<sub>2</sub>**

239 CO<sub>2</sub> emissions and removals on forest land in the LULUCF sector are generally complex, difficult to track and involve  
240 significant uncertainties, but are nonetheless highly consequential for global estimates of GHG emissions. Like land-use related  
241 CO<sub>2</sub> fluxes in general, forest fluxes share the complexity that they require modeling or other assumptions to distinguish  
242 anthropogenic from other drivers and vary concerning completeness of land-use activities represented, which contributes to large  
243 discrepancies between the various modeling and observational approaches (Obermeier et al., 2025). There are two main  
244 approaches to account for forest land fluxes: the approach developed by the IPCC guidelines and implemented in the national  
245 GHG inventories and the FAOSTAT emissions dataset, and the global bookkeeping model approach, such as the one  
246 implemented by the carbon cycle community and the Global Carbon Project. Both track changes between different types of land  
247 use (e.g. forest land, cropland, grasslands, settlements, other land) and how they influence various carbon stocks (e.g. living  
248 biomass, soil organic matter, etc.). However, they differ conceptually in one important respect: how they estimate the  
249 anthropogenic component of emissions and removals (Grassi et al., 2018, 2021, 2023; IPCC, 2024; Schwingshackl et al., 2022).  
250

251 The national GHG inventory approach is primarily survey-based and pragmatically counts all fluxes on “managed land” as  
252 anthropogenic, including both direct and indirect anthropogenic effects. Simply put, countries estimate – in line with national  
253 definitions – which areas of land are ‘managed’ in their inventories; track this area consistently over space and time; and  
254 compute the resulting fluxes as anthropogenic. All other areas and fluxes are treated as unmanaged and hence natural, and no  
255 GHG emissions or removals are reported. This convention was used as it is not easy to separate direct anthropogenic and indirect  
256 anthropogenic effects (Canadell et al., 2007; IPCC, 2006; Pongratz et al., 2021). A consequence of the inventory approach is that  
257 the quantified fluxes depend critically on the definition of “managed land”. Conventionally, “managed land” is defined in a  
258 broad sense to include land that “perform[s] production, ecological, or social functions” (IPCC, 2006, 2024). In addition to  
259 cropland, and managed forests, this may include large areas of national parks, indigenous lands or areas subject to fire-protection  
260 activities, among others (Grassi et al., 2018; Ogle et al., 2018). In the case of forests, most Annex I countries report all their land  
261 as managed (Fig. 1). Thus, in most Annex I countries, all carbon fluxes on land are considered anthropogenic, whether they are  
262 direct or indirect effects.  
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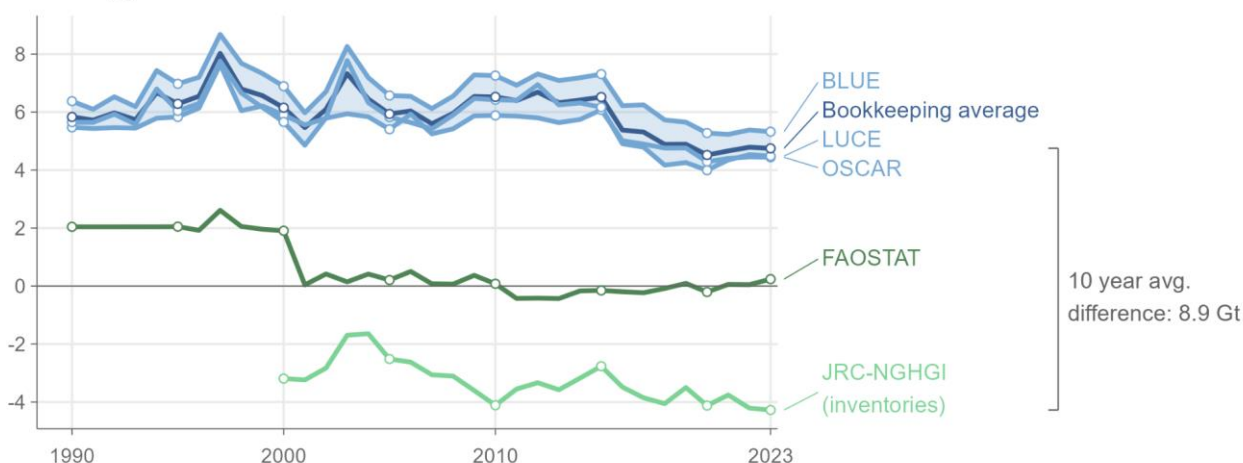
**Figure 1: Share of different land types per country.** Data: National GHG inventories.

Even within the national GHG inventory approach, important differences may arise due to use of different IPCC tier methods, despite similarities in the land use approach. These include the Tier 1 ‘gain-loss’ method (estimating fluxes due to deforestation, harvest, regrowth, etc.) and the Tier 3 ‘carbon stock change’ approach (deriving fluxes from changes in biomass stocks over time). While many country inventories, including some of those used as input into the JRC-NGHGI dataset, apply gain-loss, the FAOSTAT forest data in LULUCF are estimated using the carbon stock difference approach, using country data from the FAO Forest Resources Assessment (Tubiello et al., 2025, 2021). The application of one of the two methods brings differences in input datasets and their quality. Additional important differences between JRC-NGHGI and FAOSTAT stem from more complete coverage of sources in the former, including soils stocks, whereas the latter excludes fluxes from the soil carbon pool (Grassi et al., 2022; Tubiello et al., 2025). In particular, the forest sink is underestimated in FAOSTAT compared to JRC-NGHGI, in countries where the underlying carbon stock data is incomplete. This issue has been largely resolved due to data quality improvements in the Global Forest Resources Assessment 2025 update (FAO, 2025a).

The carbon cycle community takes a different approach to defining anthropogenic fluxes on land. Bookkeeping models are used to quantify fluxes that are the result of direct human intervention (e.g. deforestation, harvest, regrowth) (Houghton, 1999) and exclude, by simulation, those that are natural responses to human-induced environmental changes (i.e. indirect effects) - the most important of which is the increase in vegetation growth due to rising atmospheric CO<sub>2</sub> concentrations. The bookkeeping approach is independent of definitional choices related to the managed land area, as it distinguishes natural from anthropogenic fluxes not by area, but by driver (whether or not there is land-use activity). This means that implicitly all land is considered, independent of a definition of being managed or not, but fluxes only occur when land management or land-use change as defined by the models take place. Recent developments now allow the indirect fluxes of areas of land-use change to be included together with the direct flux (Friedlingstein et al., 2026).

## Differences in net land use change (LULUCF) estimates

GtCO<sub>2</sub>/year



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**Figure 2: Differences in net land use change (LULUCF) estimates.** Data: bookkeeping models BLUE, OSCAR, H&N and their average from Friedlingstein et al. (2025b) ; FAOSTAT from FAO (2025b) and Tubiello et al. (2025); Inventories from JRC-NGHGI (Melo et al., 2025). Composite data based on inventories and FAO are also available in PRIMAP-Hist, but not shown here.

The result of these conceptual differences is a gap of about 8.9 GtCO<sub>2</sub> yr<sup>-1</sup> between inventory and bookkeeping estimates of LULUCF CO<sub>2</sub> emissions (10 year average up to 2023, see Fig. 2). There are now methods to “translate” between these two approaches (Friedlingstein et al., 2025b; Grassi et al., 2018, 2023; Schwingshackl et al., 2022) - using a proxy map of countries’ managed forest - with the results documented in the JRC LULUCF data hub (Melo et al., 2025). This large difference has diverse consequences for global benchmarks of mitigation action (Gidden et al., 2023; Grassi et al., 2021), and could also have important equity implications. Thus the simple choice of national GHG inventory versus GCB data for the LULUCF sector – keeping everything else constant – can significantly affect global GHG estimates. To this regard, the IPCC (2025a) has indicated in the outlines of its AR7 reports that estimates and scenarios for human-induced, land-based CO<sub>2</sub> fluxes will need to consider alignment with national inventory definitions.

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### 2.2.2 Natural disturbances

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Fires and other disturbances occur on land, including the managed lands covered by national GHG inventories, and can generate significant emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. To illustrate, an estimated 8.8 GtCO<sub>2</sub> was released in March 2023 – February 2024 fire season, including extreme wildfires in Canada that were around 3 times more likely due to anthropogenic climate change (Jones et al., 2024b). In a stable fire regime, the vegetation on burnt areas generally recovers in subsequent years, drawing down CO<sub>2</sub> from the atmosphere during the recovery phase. In principle, this suggests that fire emissions could have a net zero impact on atmospheric CO<sub>2</sub> emissions over multiple decades under a natural fire regime (Yue et al., 2016). However, observed increases in the extent and severity of fires under climate change point to shifts in fire regimes that ultimately lead to more disturbed landscapes that store less carbon (Cunningham et al., 2024; Jones et al., 2024a).

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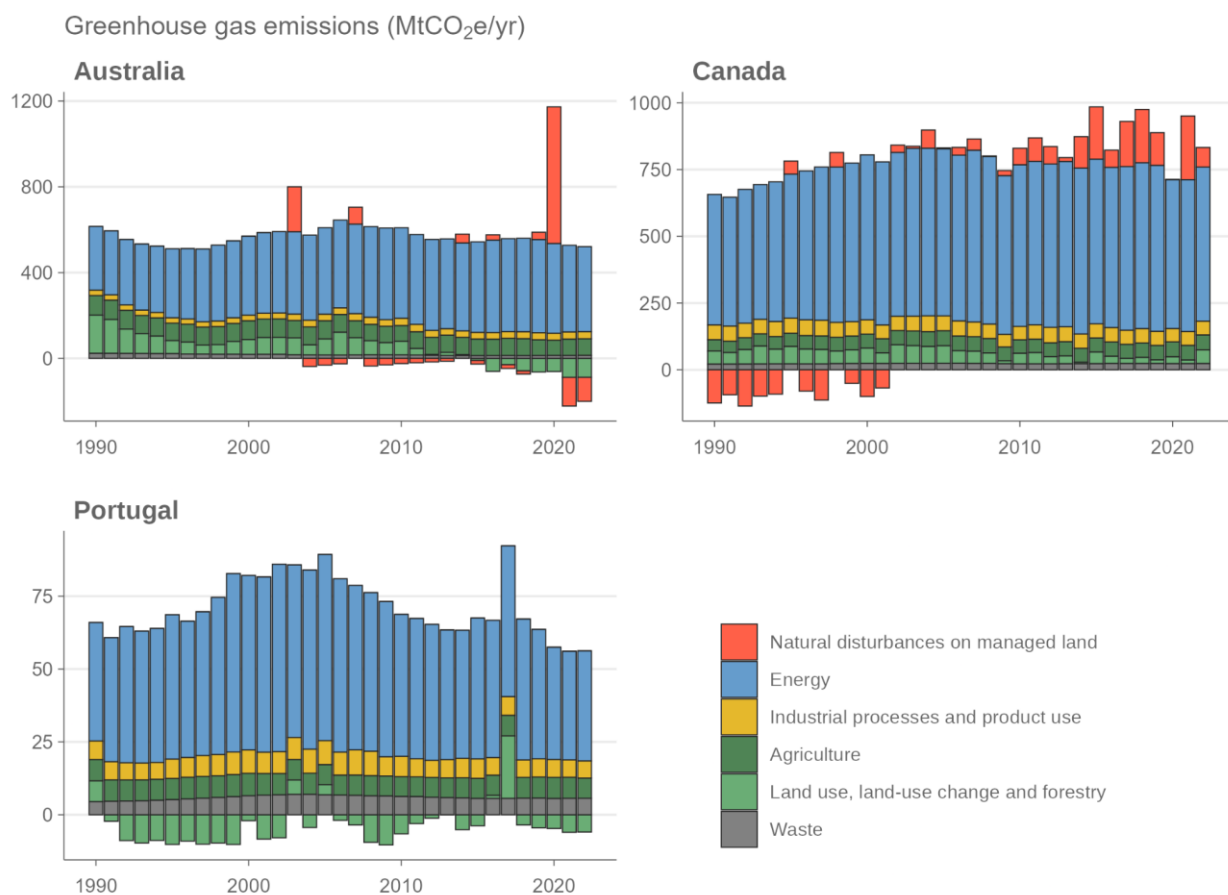
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The key problem with fires is that although they can occur naturally, they are now more likely than in the pre-industrial period due to anthropogenic climate change. This leads to major definitional obstacles to separating “anthropogenic” from “natural” fire emissions. The distinction is further complicated by the mixture of anthropogenic and natural (lightning) ignitions that occur. Anthropogenic ignitions are themselves complicated because some fires are deliberately set to clear land for agriculture or for land management purposes, or are simply the result of arson, whereas others are unintentional (e.g. power infrastructure failure or dropped cigarettes). Today’s anthropogenic ignitions must also be viewed within the context of historical rates of ignition by people, which is challenging due to poor constraints on pre-industrial fire use which lead to unreliable counterfactuals. These many complications lead to different interpretations of how fires should be accounted for in global GHG budgets. Despite this, there is a large literature and community studying fires, and numerous satellite-driven observational datasets that are used across different approaches (Giglio et al., 2013; GWIS, 2025; Kaiser et al., 2012; van der Werf et al., 2017).

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In the national GHG inventories, including FAOSTAT (Prosperi et al., 2020), CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions from fires and controlled burning (e.g. of crop residues, prescribed burning, and savannahs) are reported in the agriculture and LULUCF sectors (with the CO<sub>2</sub> emissions from some components disregarded on the assumption of equivalence between emissions and removals). In the LULUCF sector, countries either explicitly report burnt areas and their associated emissions, or they implicitly report these events in their net account of forest biomass stock changes. As discussed in the prior section, the inventories follow an area-based approach and account for all types of fires on managed land - whether they were ignited by anthropogenic or natural means, and regardless of how anthropogenic climate change has influenced their odds. In terms of reporting however, there is an important difference: in accordance with decision 18/CMA.1 §55 (UNFCCC, 2018b), countries may choose to report ‘wildfire’ events as a “natural disturbance” memo item, and exclude the associated emissions and subsequent removals from their national totals and related climate targets. So far, Australia and Canada have made use of this convention in their inventories, significantly altering the sum total of reported annual anthropogenic emissions estimates and their trends (Fig. 3). In principle, the underlying assumption in this rule is that these natural disturbance exclusions would be carbon neutral with respect to subsequent regrowth in post-fire years.



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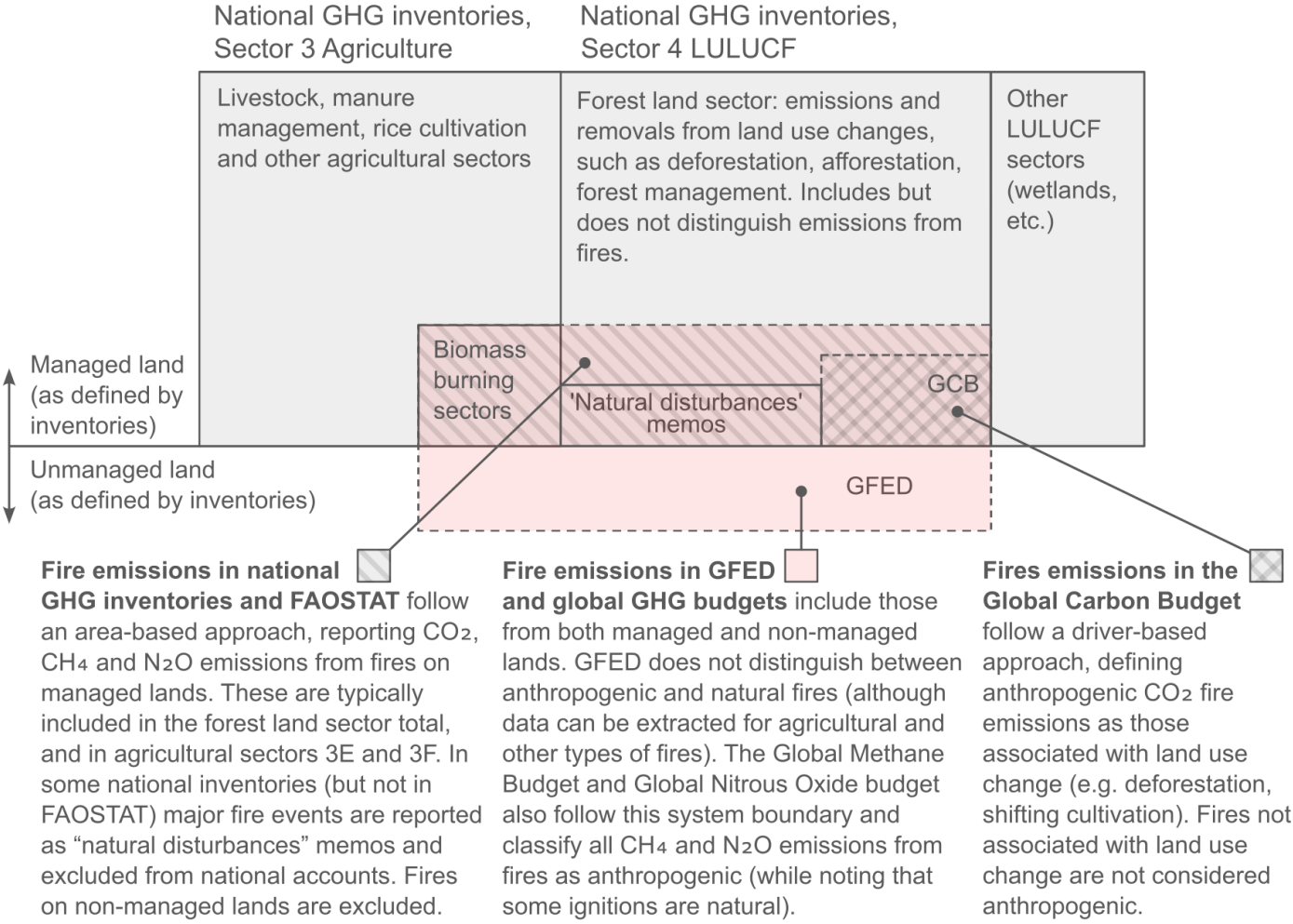
**Figure 3: Alternative approaches to accounting for wildfires in national GHG inventories.** Australia and Canada report wildfires as the memo “natural disturbances on managed land” and exclude these emissions and subsequent removals from their totals. Note that Canada started to count natural disturbances before 1990 and therefore has excluded removals in the early 1990s that occurred on previously burnt areas. Other countries have so far not used the natural disturbances memo and instead report and account for wildfires on managed land in the LULUCF sector, even in years with major events - such as Portugal in 2017. Data: National GHG inventories compiled by Lamb (2025).

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By contrast, the GCB takes a strict interpretation of ‘anthropogenic’, with CO<sub>2</sub> emissions from fires associated with anthropogenic (land-use and land management) activities included implicitly in the estimate of land-use change fluxes as part of the fluxes representing fast release of carbon to the atmosphere (as opposed to slower decomposition of material on site or as products). As the GCB defines land-use change fluxes by driver (land-use activity), these fires are often related to deforestation and shifting cultivation activities that free up land for anthropogenic use. Emissions from wildfires related to anthropogenic

350 global warming or vegetation productivity changes are not considered as part of the land-use change fluxes, but rather as an  
 351 emission term in the land sink. However, a change in climate may increase the odds that agricultural management or forest  
 352 clearing fires escape and have a larger than ‘intended’ effect (Silva Junior et al., 2020). This can be observed in, for example,  
 353 high land-use emission estimates associated with peat drainage and fires in dry El Niño years. These synergistic terms of direct  
 354 and indirect drivers are included in the GCB land-use change fluxes as part of peat drainage and peat fire emissions.  
 355 Problematically, the poor representation of the spatial distribution and trends of global fires by dynamic global vegetation models  
 356 (Jones et al., 2022; Kloster and Lasslop, 2017), as well as major fire emissions anomalies such as those linked to Canada’s  
 357 wildfires of 2023 or Australia’s Black Summer bushfires of 2019/20, leads to missing fluxes of CO<sub>2</sub> in estimates of the global  
 358 land sink and likely contributes to an imbalance in the global budget (Friedlingstein et al., 2025a; Sitch et al., 2024).  
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## Differences in fire emissions estimates

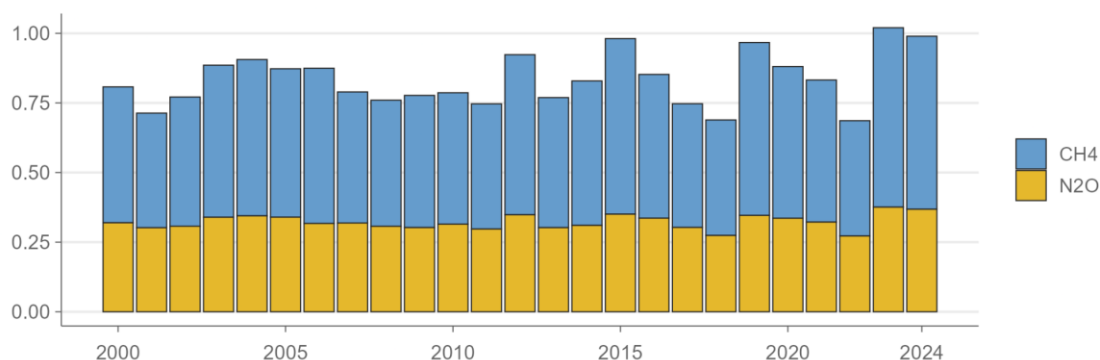


360 **Figure 4: Differences in fire emissions accounting.** Note: box areas are not representative of total fluxes in each component.  
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363 A third approach to accounting for fire emissions is represented in the Global Methane and Nitrous Oxide Budgets (Saunois et  
 364 al., 2025; Tian et al., 2024), as well as in the FAOSTAT approach (Prosperi et al., 2020) which as in the other cases typically  
 365 draw from satellite-driven observational datasets such as GFED or GFAS but do not distinguish between anthropogenic and  
 366 natural fires, nor between managed and non-managed land areas (although the GFED database categorises fires as agricultural,  
 367 deforestation and other types). In the Methane and Nitrous Oxide budgets these are known as “biomass fires” and to date have  
 368 simply been accounted as fully anthropogenic in the totals. Total annual CH<sub>4</sub> and N<sub>2</sub>O emissions from fires are significant at  
 369 approximately 0.75 GtCO<sub>2</sub>yr<sup>-1</sup> but with a highly variable trend (Fig. 5).  
 370

## Total methane and nitrous oxide emissions from fires

Gt CO<sub>2</sub>e



371  
372 **Figure 5: Global methane and nitrous oxide emissions from fires.** Data: GFEDv5.1 (van der Werf et al., 2025). CO<sub>2</sub>e emissions are  
373 calculated using GWP100 from AR6 WGI Chap. 7 (Forster et al., 2021).

### 374 2.2.3 Wetlands and freshwater body methane emissions

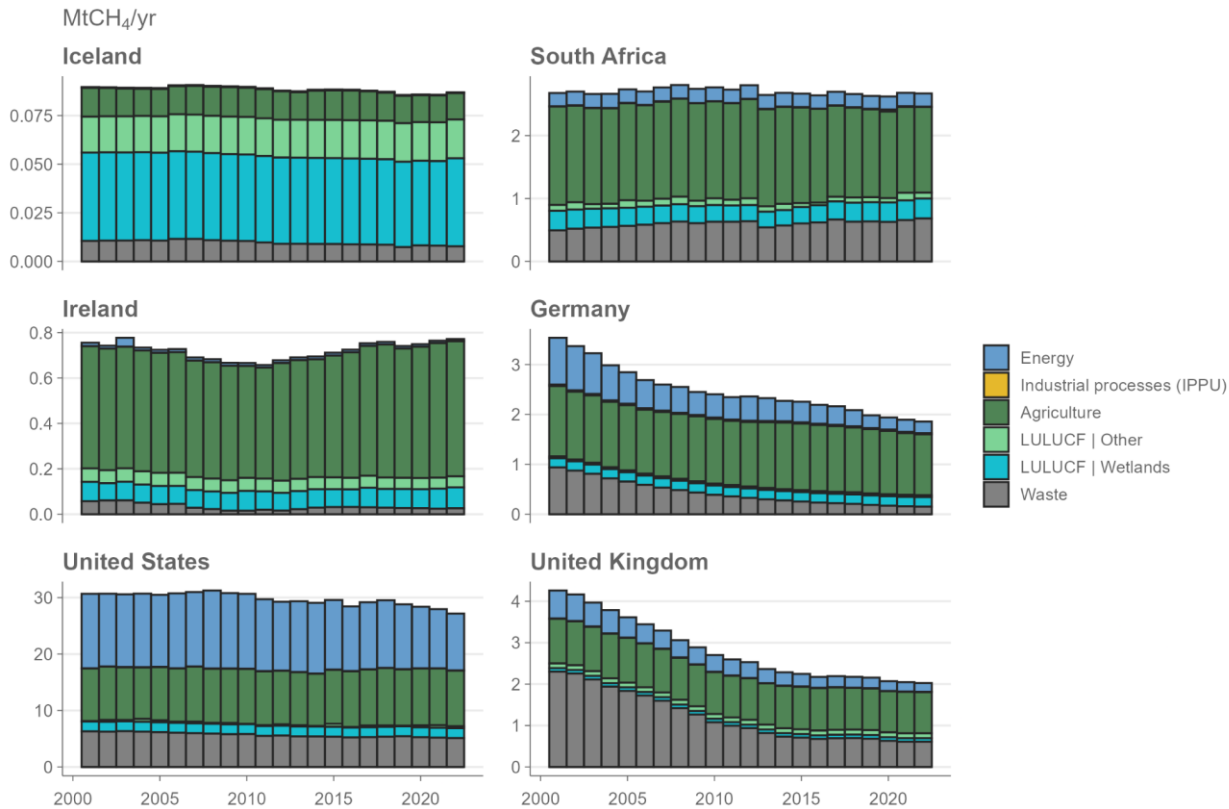
375 A range of different landscapes and land use types produce large quantities of CH<sub>4</sub> emissions via the anaerobic decomposition of  
376 organic matter. These include wetlands (e.g. peatlands, bogs, marshes) as well as freshwater bodies (reservoirs, canals, ponds,  
377 etc.). For both of these together, the Global Methane Budget reports decadal (2010 to 2019) average emissions of 248 [159 to  
378 369 min-max] MtCH<sub>4</sub> yr<sup>-1</sup> or 6.9 [4.4 to 10.3] GtCO<sub>2</sub>e yr<sup>-1</sup> (Saunio et al., 2025). In addition, N<sub>2</sub>O emissions are produced by  
379 peatland drainage. However, as in other areas of land use, there are major definitional obstacles to determining the anthropogenic  
380 component of these emissions, for example due to nutrient runoff into natural systems, as well as the influence of climate change  
381 on them.

382  
383 In the national GHG inventories, methane emissions from wetlands and freshwater bodies both fall under the LULUCF  
384 “wetlands” sector where they are restricted to managed areas of peatlands, and flooded lands resulting from artificially  
385 constructed water bodies such as reservoirs, canals, ditches and ponds. The IPCC guidelines, under the basic (Tier 1) approach,  
386 consider that methane emission changes on managed peatland are insignificant due to drainage, effectively excluding these  
387 emissions. For flooded lands, the IPCC guidance now covers methane emissions resulting from constructed water bodies and  
388 provides default emission factors based on latitudinal region to be applied to the created flooded surface. As in the case of forest  
389 land fluxes and natural disturbances, emissions from unmanaged wetlands are not estimated nor included. FAOSTAT covers  
390 only CO<sub>2</sub> and N<sub>2</sub>O emissions from peatland drainage following IPCC 2019 guidelines (Conchedda and Tubiello, 2020).

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392 The Global Methane Budget and the wider scientific community estimate wetland emissions separately based on biogeochemical  
393 models driven by the so-called wetland extent. Major uncertainties arise from difficulties in determining the extent of these areas,  
394 for example because they are under vegetated cover, or because they are in close proximity to other ecosystem types. Individual  
395 studies have estimated global emissions from reservoirs (e.g. Harrison et al., 2021; Johnson et al., 2021), rivers and streams (e.g.,  
396 Rocher-Ros et al., 2023) and lakes and ponds (e.g. Johnson et al., 2022; Zhuang et al., 2023), which are classified as inland  
397 freshwater ecosystems in the Global Methane Budget.

398  
399 Wetland and freshwater body emissions are typically classified as natural sources, even though some are artificially constructed  
400 and managed (e.g. reservoirs and farmer ponds), or are exposed to indirect anthropogenic disturbances such as eutrophication,  
401 erosion and runoff of agricultural landscapes, as well as warming. An attempt was therefore made to distinguish anthropogenic  
402 and non-anthropogenic emissions in the latest Global Methane Budget, suggesting that about half (56 of 112 Tg CH<sub>4</sub> yr<sup>-1</sup> or 1.6  
403 GtCO<sub>2</sub>e yr<sup>-1</sup>) of freshwater emissions can be classified as indirect anthropogenic emissions. Further, about 30 Tg of 159 Tg CH<sub>4</sub>  
404 yr<sup>-1</sup> or 0.8 GtCO<sub>2</sub>e yr<sup>-1</sup> of wetland emissions are considered as anthropogenic disturbances, due to restoration activities and  
405 climate feedbacks. Since few studies have estimated anthropogenic disturbances of wetland and inland freshwater emissions,  
406 such values should be taken with caution. As in the case of fires, these emissions are climate sensitive (through temperature and

407 moisture) and warming has already led to increased methane emissions from wetlands as calculated by biogeochemical models  
 408 (Zhang et al., 2025).  
 409



410  
 411 **Figure 6: Methane emissions in countries with high shares of wetland emissions.** Data: National GHG inventories compiled by Lamb  
 412 (2025).  
 413

414 Even though global anthropogenic and indirect anthropogenic CH<sub>4</sub> fluxes from wetlands and freshwater bodies are assessed to be  
 415 large at approximately 2.4 GtCO<sub>2</sub>e yr<sup>-1</sup> (based on Saunio et al. (2025), equal to 23% of methane emissions from fossil fuel  
 416 production sector, agriculture, waste and biofuel and biomass burning), national GHG inventories - which are restricted to  
 417 “artificial” water bodies on managed lands - account these emissions as very small. Figure 6 shows the CH<sub>4</sub> inventories of six  
 418 countries with the highest shares of the wetlands sector in their total CH<sub>4</sub> estimates. With the exception of Iceland (>50% share),  
 419 these emissions are trivial compared to the livestock, waste or fuel production sectors. Most countries stand at well below 1% of  
 420 their total CH<sub>4</sub> emissions from wetlands, while total wetland CH<sub>4</sub> emissions of all Annex I countries was on average 0.064  
 421 GtCO<sub>2</sub>e yr<sup>-1</sup> between 2010 and 2019, suggesting that current inventory reporting does not take into account the contributions of  
 422 eutrophication, nutrient runoff and climate feedbacks.

423 **2.3 The Paris Agreement does not cover all relevant sources of emissions**

424 The third reason why GHG estimates can differ is that current UNFCCC guidance does not cover all climatically relevant  
 425 sources of emissions and removals. This stems from the existence of other global environmental agreements and the fact that  
 426 inventory reporting guidance is not as agile in updating its scope compared to the wider literature. And since inventories exclude  
 427 certain sources and gases, this has a knock-on effect on third-party datasets that harmonise with the UNFCCC approach. Two  
 428 major current omissions are ozone depleting F-gases and the cement carbonation sink.

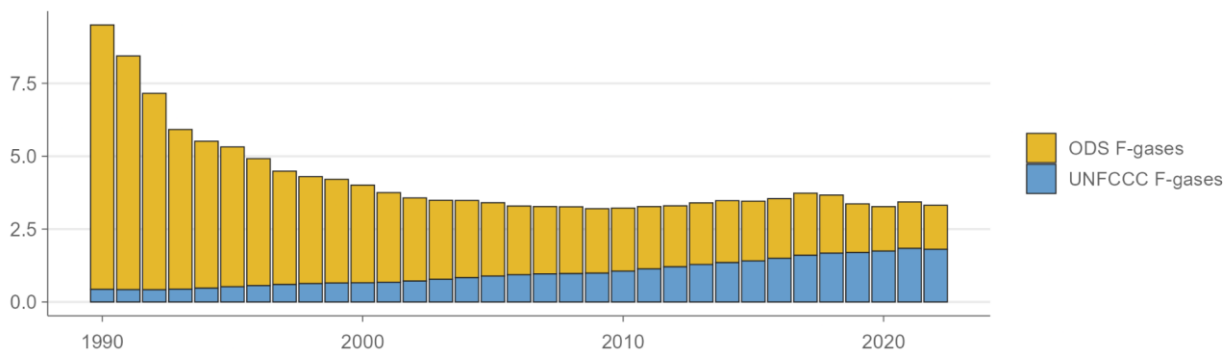
429 **2.3.1 Ozone Depleting Substances (ODS): F-gases**

430 Fluorinated gases are human made substances that are widely used in industrial processes and consumer products, for example as  
431 refrigerants, aerosols, and insulation materials. F-gases have high global warming potentials and are comprehensively assessed in  
432 the IPCC Assessment Reports (Forster et al., 2021).

433  
434 National inventory reporting and some third-party datasets include estimates of HFCs, PFCs, SF<sub>6</sub> and NF<sub>3</sub>. We call these the  
435 “UNFCCC F-gases”. (As mentioned before, the UNFCCC F-gases plus CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are often referred to as the “Kyoto  
436 gases”). However, the UNFCCC F-gases do not cover chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). We  
437 call these two categories the Ozone Depleting Substances or “ODS F-gases”. The ODS F-gases also have high global warming  
438 potentials, but were already regulated under the 1987 Montreal Protocol and the subsequent Kigali amendment because of their  
439 impacts on the ozone layer.  
440

**Total fluorinated gas emissions**

Gt CO<sub>2</sub>e



441  
442 **Figure 7: Total fluorinated (F-) gas emissions.** Data: Inversions from Forster et al. (2024). CO<sub>2</sub>e emissions are calculated using GWP100  
443 from AR6 WGI Chap. 7 (Forster et al., 2021).  
444

445 The Montreal Protocol was successful in reducing ODS F-gas emissions (Fig. 7) and consequently expected levels of global  
446 warming (Velders et al., 2007; Young et al., 2021). However, reductions have leveled off in the past decade and there is known  
447 to be a large quantity of these gases in storage and end-use devices that will continue to emit over the coming decades. As it  
448 stands, UNFCCC F-gases accounted for approximately 1.8 GtCO<sub>2</sub>e yr<sup>-1</sup> (90% CI ± 0.54) in 2022, while ODS F-gases contributed  
449 1.5 GtCO<sub>2</sub>e yr<sup>-1</sup> (90% CI ± 0.45) (Forster et al., 2024). Thus, while all emissions of F-gases can be well estimated using top-  
450 down methods - since there are no natural sources and they only break down chemically - typical reporting of global and national  
451 emissions estimates only includes a portion of them, simply because ODS F-gases are excluded from UNFCCC reporting.

452 **2.3.2 Cement carbonation**

453 Atmospheric CO<sub>2</sub> is gradually absorbed into cement materials that are exposed to air, a process known as cement carbonation.  
454 This is a slow process over decades, but a globally significant one, because of the enormous quantity of cement that is produced  
455 and used in the built environment.  
456

457 The GCB tracks the global cement carbonation sink (Friedlingstein et al., 2025b), which itself is based on a bottom-up  
458 assessment of cement production and use statistics (Huang et al., 2023). Current estimates indicate a global sink of 0.8 GtCO<sub>2</sub> yr<sup>-1</sup>  
459 that has steadily and rapidly increased alongside cement production. This is currently sufficient to compensate for about one  
460 third of cement process emissions (Huang et al., 2023). However, uncertainty is currently large, particularly due to lack of data  
461 on the share of cement that is used for concrete versus mortar, which are products with very different rates of carbon uptake.  
462

463 Cement carbonation has historically not been included in national GHG inventories, since it has not been covered by the IPCC  
464 inventory guidelines and refinements. It is therefore technically, but not formally, excluded from the Paris Agreement. However,  
465 this is not from lack of interest from governments. Sweden has reported a Tier 1 cement carbonation calculation and memo in its

466 National Inventory Report since 2020, but excludes this from its submitted inventory account. The UK has also recently  
467 published a Tier 2 methodology (DESNZ, 2023). The IPCC is expected to soon begin work on including a new chapter  
468 specifically on carbonation of both cement and lime in the Guidelines, as part of a new supplement to the 2006 Guidelines  
469 (IPCC, 2025b). Once in the IPCC Guidelines, there is a clearer path for inclusion in national inventories. In third-party datasets  
470 of national emissions, cement carbonation is not included, but estimates of national totals have recently been published (Niu et  
471 al., 2024).

472

473 One question that the inclusion of cement and lime carbonation raises is whether it is a sink that can be directly and intentionally  
474 modified, given that it is something that occurs to substances that have been already produced in the past (much like the concept  
475 of “indirect anthropogenic effects” in the land use sector). Currently most concrete structures are designed to minimise  
476 carbonation, because it often leads to structural weaknesses. Changes in design and cement composition (e.g. to allow the use of  
477 aluminium reinforcing instead of steel) could lead to less focus on mitigating carbonation, and hence greater absorption of CO<sub>2</sub>.  
478 Further, at the end of a structure’s life, when concrete is demolished, whether that concrete rubble is buried without access to air  
479 or not has a large effect on further uptake, and this is something that could be controlled.

### 480 **3 Conventions to assess emissions in different communities**

481 For any given assessment of emissions, there are clearly many different decisions to be made regarding scope, system boundaries  
482 and the selection of appropriate data. In this section, we therefore discuss how and why these choices are made in several  
483 different assessment communities that are involved in estimating, tracking or using GHG emissions data. These different  
484 conventions and their implied data choices are summarised in Fig. 8.

#### 485 **3.1 National targets, pledges and inventories under the UNFCCC**

486 Countries are obligated to formulate climate targets, strategies and policies under the UNFCCC, most notably the Nationally  
487 Determined Contributions (NDCs), which define their pledges to reduce emissions in the coming decades. The NDCs are one of  
488 the core mechanisms of the Paris Agreement and are formally linked to the national GHG inventories: where countries pledge  
489 emissions reductions with reference to their historic emissions (e.g. a baseline level), that information should be in accordance  
490 with IPCC conventions and their national GHG inventories (UNFCCC, 2018a, 2022a). Similarly, national net zero targets are all  
491 based on inventory conventions. This ensures some degree of consistency in the agreement and encourages all countries to  
492 pledge emissions reductions in the same set of sectors, sources and gases, under the same definitions (e.g. of anthropogenic vs.  
493 natural sources and sinks).

494

495 A consequence of this framework for the research community and the IPCC is that independent assessments of current policy  
496 projections, the NDCs and net zero targets must also follow inventory conventions. This means that the data should cover the  
497 same scope of sectors and gases as inventories, and that LULUCF estimates follow the inventory approach. Since ODS F-gases  
498 and cement carbonation currently lie outside of the agreement, they must be excluded or treated separately. Similarly, it implies  
499 that fires not occurring on managed land do not matter for target achievement, and that countries are able to define their approach  
500 to excluding natural disturbances (Australia and Canada have already done so in their NDCs with reference to their GHG  
501 inventory conventions, see above). Finally, international aviation and shipping emissions are something of a grey area under the  
502 agreement, as they are reported as memos in national inventories, but are not accounted in totals nor towards national target  
503 achievement. Together, these requirements lead to a handful of options for tracking emissions in line with the inventory  
504 approach: the PRIMAP Hist-CR dataset; the EDGAR dataset in combination with JRC-NGHGI (for CO<sub>2</sub> LULUCF), or national  
505 GHG inventories when dealing with individual or Annex I countries.

506

507 In practice, assessments of national pledges are particularly complicated by the LULUCF sector. The official synthesis of NDC  
508 emissions projections prepared by the UNFCCC secretariat excludes inventory-based LULUCF emissions (UNFCCC, 2022b). In  
509 the scientific literature, emissions projections of the NDCs and current policies also tend to avoid the LULUCF sector  
510 (Meinshausen et al., 2022), or carefully deal with it separately (Den Elzen et al., 2022). This is due to both ambiguity in the  
511 LULUCF contribution towards the targets of many countries (Fyson and Jeffery, 2019), as well as definitional differences  
512 between the inventory and bookkeeping approach (section 2.2), which is consequential for benchmarking the NDCs against

513 integrated assessment models. By contrast, UNFCCC reporting on historical emissions includes LULUCF, following the national  
514 inventory approach (UNFCCC, 2022c). The UNEP Emissions Gap Reports have also been reporting emissions at the national  
515 level including inventory-based LULUCF for several years - alongside a global total aligned with integrated assessment  
516 modelling benchmarks (see next section) (UNEP, 2022, 2023, 2024). Indeed, detailed analyses of LULUCF pledges shows it is  
517 an important sector from the perspective of countries, both in their short and long-term targets (Grassi et al., 2017; Roman-  
518 Cuesta et al., 2024). Thus while analyses focusing on national targets and pledges generally agree on the scope of emissions to  
519 assess, approaches to LULUCF can differ.

### 520 **3.2 Integrated assessment modelling benchmarks**

521 Another key area where emissions assessments take place is in the integrated assessment modelling (IAM) literature. IAMs are  
522 used to derive future emissions scenarios under different assumptions of technology development and policy action, which then  
523 inform projections of climate change in the coming decades. IAMs therefore model future rather than past GHG emissions, but  
524 do so in accordance with a specific scope and set of system boundaries, and are often calibrated by or are compared to historic  
525 estimates of emissions (e.g. in terms of projected emission reduction rates). Notably, benchmarks from IAMs (e.g. describing  
526 emissions levels or reductions in the future that lead to different climate outcomes) are reported in the IPCC and are widely used  
527 to contextualise national or global progress towards the temperature goals of the Paris Agreement (IPCC, 2022; UNEP, 2024).  
528

529 There are over a dozen different IAMs that regularly contribute to the literature, with significant heterogeneity in model structure  
530 and scope. Nonetheless, they tend to follow several key conventions. First, most IAMs model the same basket of greenhouse  
531 gases as national GHG inventories: the Kyoto gases. Emissions reporting is also often split into a similar set of sectors as in  
532 national inventories and third-party emissions datasets (Byers et al., 2022). However, not all IAMs contain a land use model and  
533 therefore some exclude the LULUCF sector. Beyond the Kyoto gases, many IAMs also include aerosols and other precursor  
534 species with climate effects. IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE and GCAM do not report ODS F-gases (The  
535 common Integrated Assessment Model (IAM) documentation, 2025). Most IAMs do not incorporate cement carbonation, though  
536 MESSAGE and IMAGE do. Second, and related to the LULUCF sector, IAMs typically only model anthropogenically induced  
537 emissions. This follows from the basic purpose of IAMs, which is to analyse how human-driven technology and policy options  
538 can shape the future climate response. Where a land use model is included, they predominantly consider direct anthropogenic  
539 effects only associated with agriculture, land-use, land-use change or forestry (as in the Global Carbon Budget bookkeeping  
540 approach), and do not include climate and fertilisation effects, particularly in forests remaining forests. Nonetheless, IAMs  
541 continue to be improved to represent other emissions sources on land, both direct and indirect, including peatland rewetting, fire  
542 emissions, and others.  
543

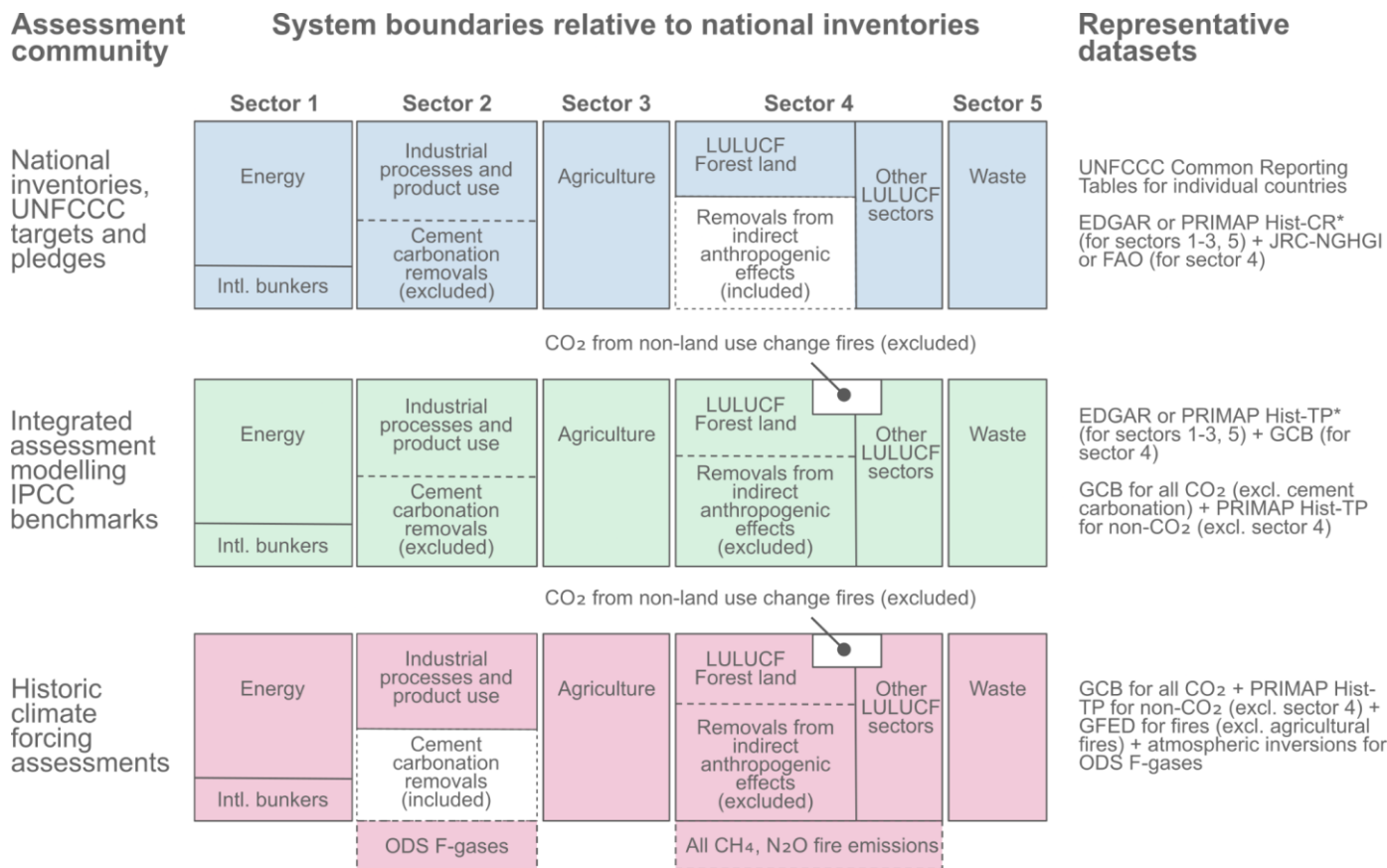
544 Different IAM groups use different historical emissions data to calibrate their models, and the calibration is often done for  
545 consistency and not for replication. There have been attempts to harmonise energy and emissions input data across models  
546 (Giarola et al., 2021) and protocols written for various projects (Korsbakken et al., 2024), but because of differences in model  
547 structure, it is not always possible or desirable to harmonise. To perform consistent climate assessments across multiple models it  
548 is therefore necessary to post-process IAM emissions data, in-filling missing gases or sectors where necessary (Kikstra et al.,  
549 2022). Post-processed IAM results form the backbone of IPCC benchmarks of global action, such as the timing of net zero  
550 emissions required to meet different climate objectives. To date these assessments have been aligned with the set of gases and  
551 sectors outlined in inventories and the Paris agreement, but with the important difference that they use bookkeeping conventions  
552 for the LULUCF sector. Other (e.g. non-Paris) emissions or land-based fluxes, as well as aerosols and precursor species, may be  
553 modelled within IAMs, but these would be excluded from the benchmarks. This means that IAM benchmarks cannot be directly  
554 compared to NDC assessments, but post processing can be used to translate between the two (Gidden et al., 2023; Grassi et al.,  
555 2021), as IAMs do not yet do this modelling natively. The translation and comparison of native IAM results to national inventory  
556 definitions is already foreseen in the IPCC AR7 report outline. This is needed to emphasize the consequences of different  
557 definitions: after IAM results are translated to national inventory definitions, the carbon budget is reduced (Gidden et al., 2023;  
558 Grassi et al., 2021) and reaching net-zero CO<sub>2</sub> alone will not suffice to prevent global warming (Allen et al., 2025).

559 **3.4 Climate forcing assessments**

560 A third area of emissions assessments takes the atmosphere as the primary frame of reference, in contrast to national accounts  
 561 and IAM benchmarks. The main objective of these is to track and explain observed changes to atmospheric concentrations of  
 562 greenhouse gases, to evaluate their influences on the climate (for instance through effective radiative forcing (ERF) estimates), or  
 563 to develop forward looking climate projections (Forster et al., 2024; Smith et al., 2021, 2024). They may also include emissions  
 564 budgeting studies and related publications that aim to track both natural and anthropogenic fluxes of emissions to the atmosphere  
 565 (Friedlingstein et al., 2025b; Saunois et al., 2025; Tian et al., 2024; UNEP and CCAC, 2021). All are closely related to the  
 566 climate modelling literature.

567  
 568 Since these assessments aim to get the best estimate of GHG fluxes to the atmosphere, they would consider non-Paris Agreement  
 569 sources (ODS F-gases and cement carbonation) as well as all (non-CO<sub>2</sub>) fire emissions. (Note that aerosol precursor species and  
 570 other short-lived climate forcers would also be considered relevant for these assessments). Removals due to natural sinks are  
 571 generally not considered as input data, as they are modelled directly by the climate models themselves, partly because these sinks  
 572 are functions of the climate state and hence are considered part of climate feedbacks. Additionally, climate modelling requires  
 573 inputs starting from pre-industrial, usually 17- or 1850, meaning that long time series datasets are often prioritised. Unless  
 574 studies are explicitly considering national boundaries or contributions to climate change (e.g. as in Jones et al., 2023), detailed  
 575 national or sectoral data is usually not required. This relaxes some constraints on using top-down observational datasets (e.g. fire  
 576 emissions observations, inversions of atmospheric concentrations), which often cannot be easily assigned to territorial  
 577 boundaries. These considerations lead to a few key sources being used for historical emissions: the GCB for CO<sub>2</sub>, CEDS or  
 578 PRIMAP Hist-TP datasets for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions, the GFED dataset for CH<sub>4</sub> and N<sub>2</sub>O from fires, and inversion  
 579 datasets (e.g. Velders et al., 2015; WMO, 2022) for F-gases (both UNFCCC and ODS).

580



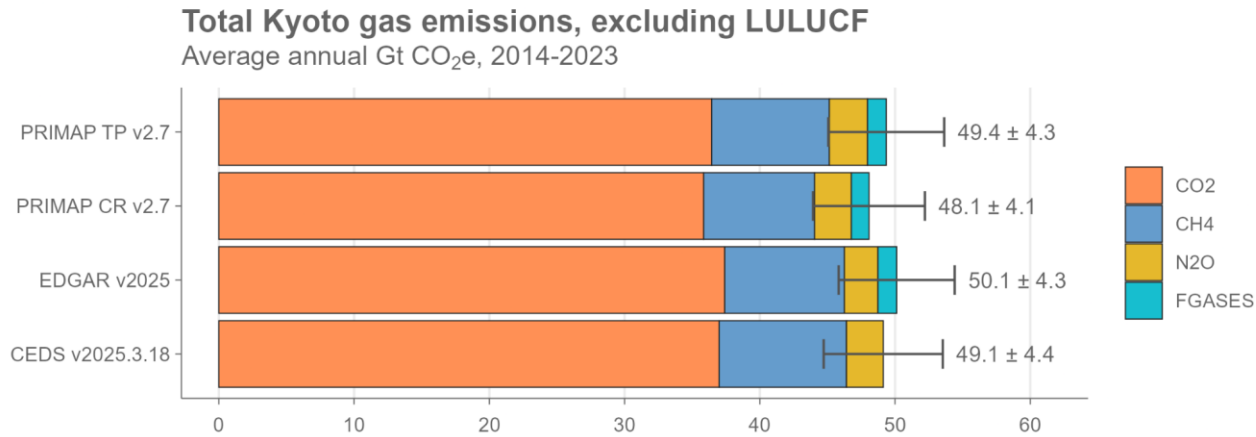
581  
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 585

**Figure 8: Differences in greenhouse gas emissions conventions for three assessment communities.** Box sizes are not representative of total emissions in each component. Notes: \* PRIMAP Hist excludes international bunkers, but these could be added using the GCB or EDGAR datasets.

586 **4 Comparison and spread of GHG estimates**

587 To what extent do the discussed issues of dataset coverage, definitions of anthropogenic emissions, and scope of the Paris  
588 Agreement influence total GHG estimates?

589  
590 In the first instance, only a handful of datasets come close to a complete coverage of inventory sectors and gases. For all Kyoto  
591 gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and UNFCCC F-gases) and excluding the LULUCF sector, these include PRIMAP Hist-TP, PRIMAP  
592 Hist-CR and EDGAR. A fourth dataset covers these gases but excludes F-gases: CEDS. Between these datasets we observe  
593 relatively minor deviations in total average decadal GHG emissions, the largest of which is due to differences in CH<sub>4</sub> estimates  
594 between PRIMAP Hist-CR and PRIMAP Hist-TP (Fig. 9).  
595

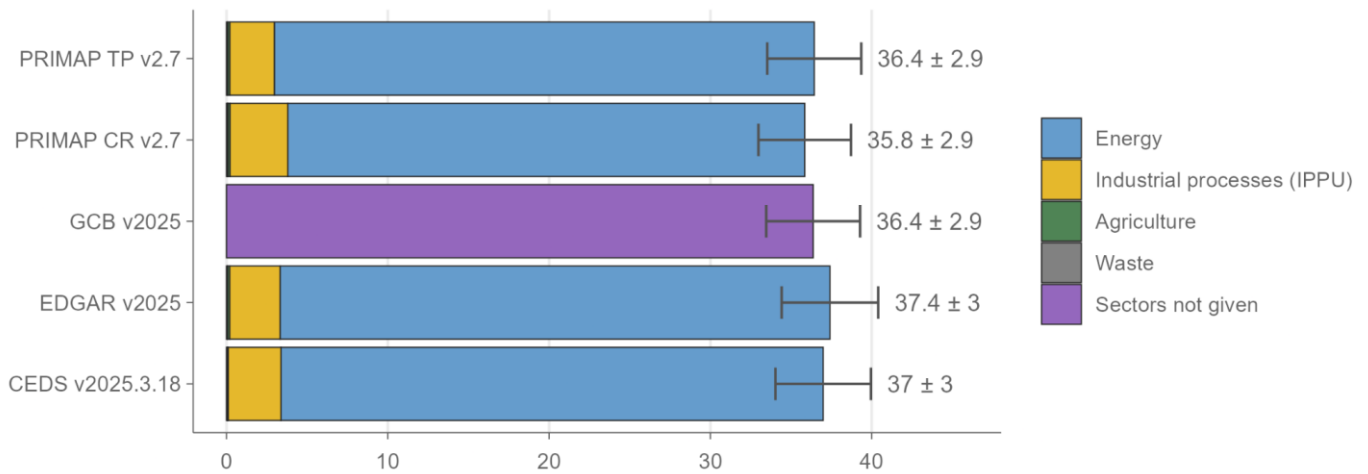


596  
597 **Figure 9: Total Kyoto gas emissions across datasets, excluding LULUCF.** Kyoto gases refer to CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and UNFCCC F-gas  
598 emissions. Error bars indicate composite uncertainties of ±8 % for CO<sub>2</sub> (excl. LULUCF), ±30 % for CH<sub>4</sub> and F-gases, and ±60 % for N<sub>2</sub>O,  
599 corresponding to a 90 % confidence interval following Minx et al. (2021). CO<sub>2</sub>e emissions are calculated using GWP100 from AR6 WGI Chap.  
600 7 (Forster et al., 2021). Note that the PRIMAP datasets exclude international bunker emissions.  
601

602 Considering CO<sub>2</sub> emissions separately, we observe a low relative spread between datasets that cover a similar set of system  
603 boundaries, but absolute differences of up to 2.05 GtCO<sub>2</sub> yr<sup>-1</sup> (e.g. between the lowest estimate from PRIMAP Hist-CR and the  
604 highest from EDGAR; Fig. 9). Relative differences as well as uncertainties are higher for CH<sub>4</sub> and N<sub>2</sub>O emissions, with PRIMAP  
605 Hist-CR - the PRIMAP time series that prioritises national inventory data - in particular reporting lower fossil CH<sub>4</sub> emissions  
606 (Fig. 11 to 12). Indeed, several studies have pointed to relatively low estimates of fossil CH<sub>4</sub> in national inventories compared to  
607 observational evidence (Deng et al., 2022; Janardanan et al., 2024; Scarpelli et al., 2022; Tibrewal et al., 2024).

### Total carbon dioxide emissions, excluding LULUCF

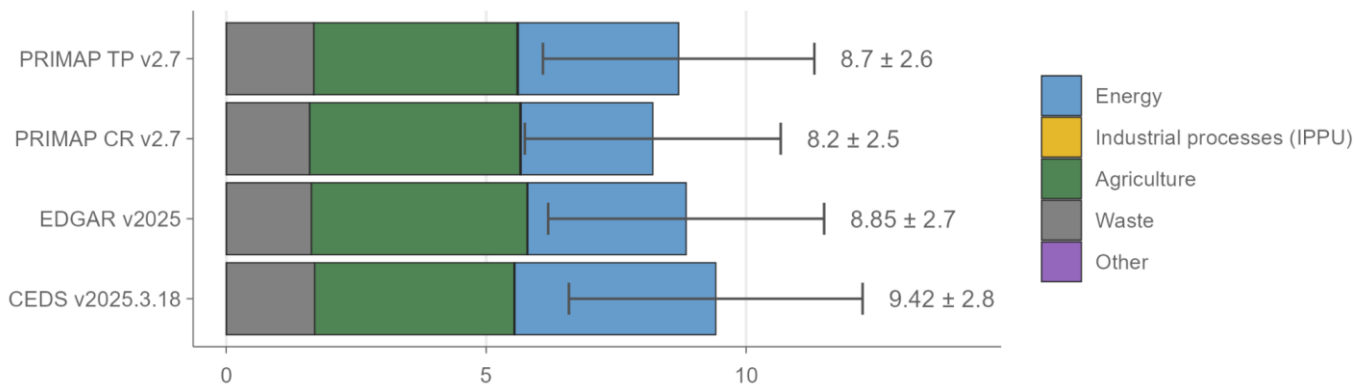
Average annual Gt CO<sub>2</sub>, 2014-2023



608  
 609 **Figure 10: Total carbon dioxide emissions across datasets, excluding LULUCF.** Error bars indicate uncertainties of ±8 % for CO<sub>2</sub> (excl.  
 610 LULUCF), corresponding to a 90 % confidence interval following Minx et al. (2021). Note that the PRIMAP datasets exclude international  
 611 bunker emissions, and that the GCB estimate excludes cement carbonation.  
 612

### Total methane emissions, excluding LULUCF

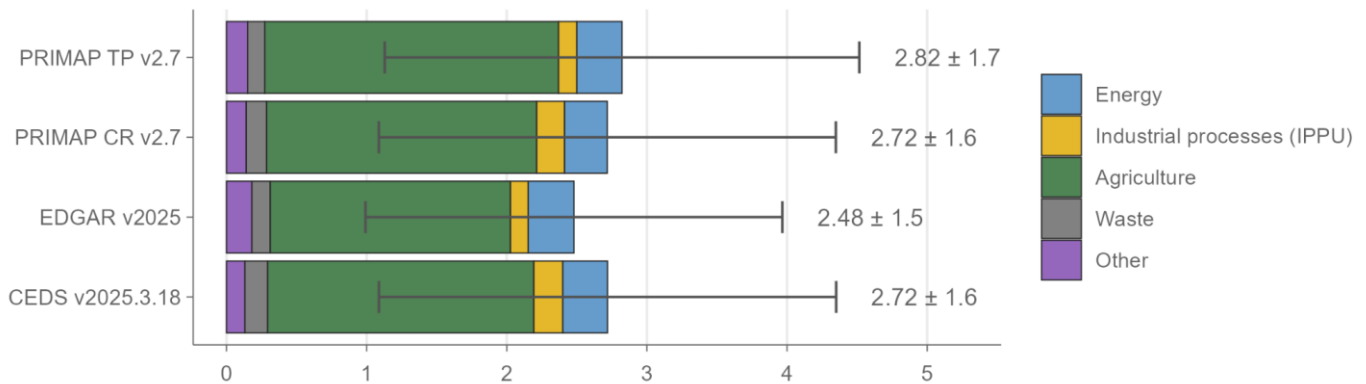
Average annual Gt CO<sub>2</sub>e, 2014-2023



613  
 614 **Figure 11: Total methane emissions across datasets, excluding LULUCF.** Error bars indicate uncertainties of ±30 % for CH<sub>4</sub> (excl.  
 615 LULUCF), corresponding to a 90 % confidence interval following Minx et al. (2021). CO<sub>2</sub>e emissions are calculated using GWP100 from AR6  
 616 WGI Chap. 7, here with a value of 27.9 (Forster et al., 2021).  
 617

### Total nitrous oxide emissions, excluding LULUCF

Average annual Gt CO<sub>2</sub>e, 2014-2023

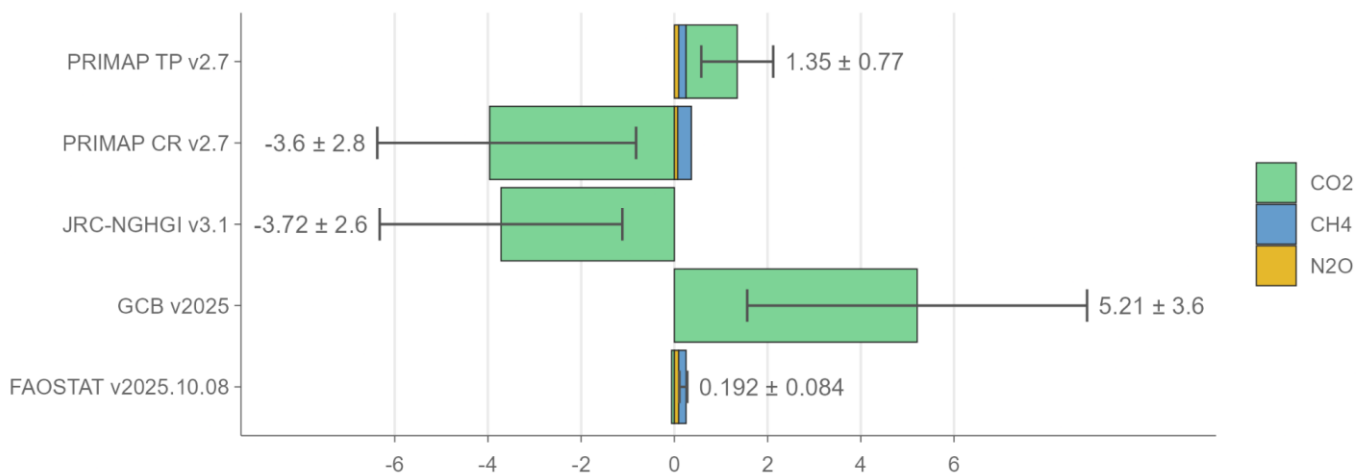


618  
619 **Figure 12: Total nitrous oxide emissions across datasets, excluding LULUCF.** Error bars indicate uncertainties of  $\pm 60\%$  for N<sub>2</sub>O (excl.  
620 LULUCF), corresponding to a 90 % confidence interval following Minx et al. (2021). CO<sub>2</sub>e emissions are calculated using GWP100 from AR6  
621 WGI Chap. 7 (Forster et al., 2021).  
622

623 By far the largest differences between datasets can be observed in the LULUCF sector (Fig. 13). According to decadal averages,  
624 these range from net negative emissions of -3.72 to -3.6 GtCO<sub>2</sub>e yr<sup>-1</sup> in the two national inventory aligned datasets (JRC-NGHGI  
625 and PRIMAP Hist-CR), to net positive emissions in FAO (0.192 GtCO<sub>2</sub>e yr<sup>-1</sup>) and its derivative, PRIMAP Hist-TP (1.35 GtCO<sub>2</sub>e  
626 yr<sup>-1</sup>), to significantly larger net emissions in the GCB (5.21 GtCO<sub>2</sub>e yr<sup>-1</sup>). As described in section 2.2, JRC-NGHGI and GCB  
627 differ conceptually in terms of how they define anthropogenic removals and how they treat natural disturbances. And as noted by  
628 Grassi et al. (2022) the forest sink may be underestimated in FAOSTAT, in those countries where the underlying input data is  
629 incomplete. Of the datasets above, only some of them (FAOSTAT and its derivative PRIMAP) include non-CO<sub>2</sub> emissions from  
630 fires and other land uses.  
631

### Total LULUCF emissions

Average annual Gt CO<sub>2</sub>e, 2014-2023



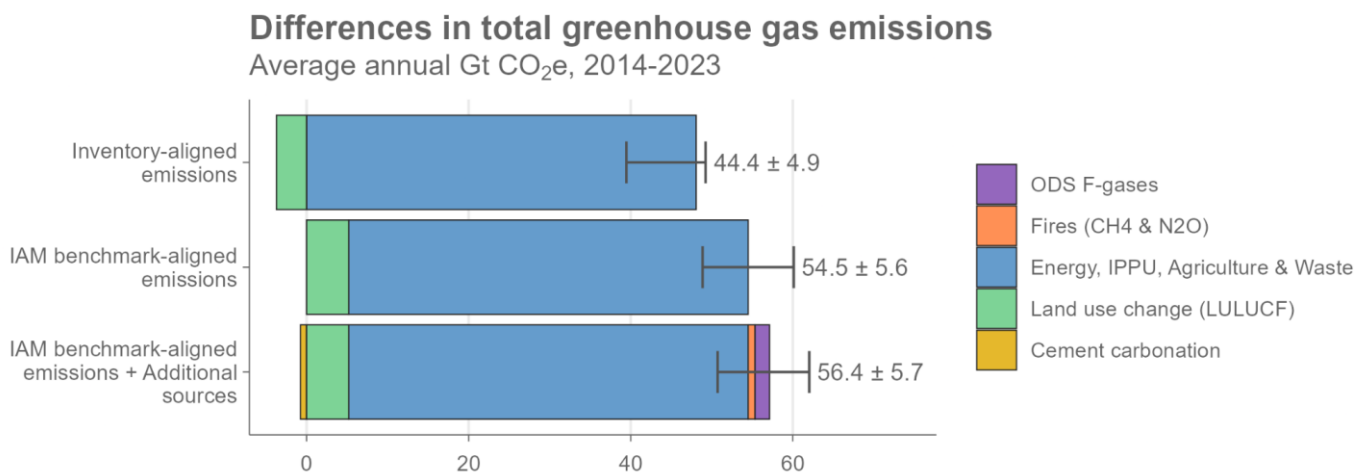
632  
633 **Figure 13: Total LULUCF emissions across datasets.** Error bars indicate uncertainties of  $\pm 70\%$  for CO<sub>2</sub> LULUCF,  $\pm 30\%$  for CH<sub>4</sub> and  $\pm 60\%$   
634 % for N<sub>2</sub>O, corresponding to a 90 % confidence interval following Minx et al. (2021). CO<sub>2</sub>e emissions are calculated using GWP100 from AR6  
635 WGI Chap. 7 (Forster et al., 2021).  
636

637 Comparing emissions across the three assessment conventions outlined in section 3 (summarised in Fig. 8), significant  
638 differences in total global greenhouse gas emissions can be observed (Fig. 14). Inventory-aligned emissions, shown here using

639 PRIMAP Hist-CR for non-LULUCF sectors and JRC-NGHGI for LULUCF, were 44.4 GtCO<sub>2</sub>e yr<sup>-1</sup> [90% CI ± 4.9] in the decade  
 640 2014-2023. These emissions are both low relative to third-party datasets in terms of fossil methane, exclude international  
 641 aviation and shipping, and include the inventory-aligned definition of LULUCF. This is ~10.1 GtCO<sub>2</sub>e yr<sup>-1</sup> lower than emissions  
 642 comparable with IAM benchmarks, primarily due to the bookkeeping definition of LULUCF (~8.9 GtCO<sub>2</sub>e yr<sup>-1</sup>), but also due to  
 643 lower estimates of fossil methane in inventory prioritised data, as well as the inclusion of bunker emissions (the latter adding 1.1  
 644 GtCO<sub>2</sub> yr<sup>-1</sup> between 2014-2023). Expanding the scope further to consider non-Paris sources (ODS F-gases, cement carbonation)  
 645 and all global fire emissions of CH<sub>4</sub> and N<sub>2</sub>O, decadal average emissions increase by 1.9 GtCO<sub>2</sub>e yr<sup>-1</sup>, of which 1.8 GtCO<sub>2</sub>e yr<sup>-1</sup> is  
 646 from ODS F-gases, -0.75 GtCO<sub>2</sub> yr<sup>-1</sup> is from the cement carbonation sink, and 0.85 GtCO<sub>2</sub> yr<sup>-1</sup> is from fires. Interannual  
 647 variability in emissions also increases due to large fluctuations in annual fire emissions (Fig. 5).

649 The emissions shown in Figure 14 do not include non-CO<sub>2</sub> emissions in the LULUCF sector, which based on FAOSTAT would  
 650 be 0.25 GtCO<sub>2</sub> yr<sup>-1</sup>. Further, none of the datasets in Figure 14 (nor FAOSTAT) include the indirect anthropogenic portion of  
 651 emissions from wetlands or freshwater bodies, which aggregated and estimated from individual studies may sum to as much as  
 652 2.4 GtCO<sub>2</sub> yr<sup>-1</sup> as discussed in section 2.2.3.

653



654 **Figure 14: Differences in total greenhouse gas emissions under different data and system boundary choices.** Error bars indicate  
 655 uncertainties of ±8% for CO<sub>2</sub> Fossil, ±70 % for CO<sub>2</sub> LULUCF, ±30 % for CH<sub>4</sub> and ±60 % for N<sub>2</sub>O, corresponding to a 90 % confidence  
 656 interval following Minx et al. (2021). CO<sub>2</sub>e emissions are calculated using GWP100 from AR6 WGI Chap. 7 (Forster et al., 2021). Data: for  
 657 ‘inventory-aligned emissions’ PRIMAP Hist-CR (non-LULUCF sectors) and JRC-NGHGI (LULUCF) (Gütschow et al., 2025; Melo et al.,  
 658 2025); for ‘IAM benchmark-aligned emissions’ GCB (all CO<sub>2</sub> incl. LULUCF) and PRIMAP Hist-TP (non-CO<sub>2</sub>, excl. LULUCF)  
 659 (Friedlingstein et al., 2025b; Gütschow et al., 2025); for ‘Additional sources’ Forster et al. (ODS F-gases), GFED (fires) and GCB (cement  
 660 carbonation) (Forster et al., 2024; Friedlingstein et al., 2025b; van der Werf et al., 2017). The order of the bars does not presuppose any  
 661 preferences for which approach should be used, which depends on the research question, aims and context of an assessment.  
 662

## 663 5 Discussion and conclusion

664 In this article we have explored key reasons why GHG emissions estimates differ, namely that datasets vary in their coverage of  
 665 gases, sectors and countries; that there are different approaches to defining ‘anthropogenic’ emissions; and that the Paris  
 666 Agreement doesn’t cover all relevant sources of emissions. Importantly, we find that there are multiple possible approaches to  
 667 addressing these issues, and that these depend on different decision criteria determining the scope and conceptual boundaries of  
 668 an assessment. Among the assessment conventions we have described, such criteria include *political relevance* (where an  
 669 assessment aims to be consistent with the scope of the Paris Agreement), that emissions should be *direct anthropogenic only*  
 670 (where an assessment excludes sources and sinks that are less amenable to direct policy intervention), or that emissions should be  
 671 *accurate compared to observations* (where an assessment aims to describe the best estimate of fluxes consistent with  
 672 observations). Other decision criteria are also possible, some of which are mutually exclusive or in conflict with one another  
 673 (Table 2). This underlines the importance of clearly stating which criteria drive an assessment, and what they imply in terms of  
 674 emissions coverage and system boundaries.

Relevant decision criteria	Description	Example use cases
Pragmatism	Datasets are chosen that are relatively up-to-date and complete, open source and easily machine readable, provide a reasonable level of national or sectoral detail, but do not necessarily use high tier estimation methods	Ex-post evaluations of climate policy effectiveness (Stechemesser et al., 2024)
Political relevance	Datasets should be officially recognised by parties to the UNFCCC, can be estimated by countries with varying institutional capacities, and are consistent with those used to inform national emission reduction pledges	Evaluations of implied emissions reductions under climate pledges, the NDCs or national net zero targets (Den Elzen et al., 2022)
Consistency	Datasets are chosen to be consistent with the frameworks and uses of the respective assessment community, for example to harmonise with definitions of “net zero”, or use consistent assumptions as taken in the IPCC	Updates of IPCC indicators (Forster et al., 2024)
Direct anthropogenic only	Datasets and their sources are conceptually limited to only the set of activities that are directly human driven and thereby amenable to policy intervention	Integrated assessment modelling benchmarks and bookkeeping land use change models (UNEP, 2024)
Accuracy compared to observations	The group of sources, including indirect anthropogenic emissions, that gives the best estimate of the flux to the atmosphere compared to observations	Greenhouse gas budgeting studies (Friedlingstein et al., 2025b; Saunio et al., 2025; Tian et al., 2024)
Time series since pre-industrial	Analysis is dependent on a time series since pre-industrial (e.g. 1750 or 1850)	Modelling of historic contributions to climate change (Jones et al., 2023)

676 **Table 2: Decision criteria for selecting and using emissions data.**

677

678 For some components of emissions, it is straightforward to quantify the impact of including or excluding them from totals. This  
679 is the case for ODS F-gases, cement carbonation, as well as for the LULUCF sector where significant efforts have been made to  
680 explain differences and provide translation methodologies between estimates (Friedlingstein et al., 2025b; Grassi et al., 2023;  
681 Schwingshackl et al., 2022). However, for others the impact of different conceptual approaches is more challenging to quantify.  
682 For instance, while the broad treatment of fire emissions in inventories, models and third-party datasets is known (Fig. 3),  
683 quantifying these differences would require directly comparing their estimates of burned areas and emissions within the  
684 LULUCF sector. While this is largely available in the national GHG inventories, these are globally incomplete. Further,  
685 observational datasets such as GFED do not differentiate by national borders; while others (e.g. FAO, GCB, PRIMAP-Hist) do.  
686 Similarly, in the case of wetlands and freshwater bodies, there are estimates in literature on global fluxes, but little work on  
687 comparing these to bottom-up, national or inventory estimates - although such comparisons have been made for N<sub>2</sub>O (Conchedda  
688 and Tubiello, 2020). As a result, differences in how datasets treat indirect anthropogenic fluxes from fires and wetlands are  
689 largely unknown to non-domain experts. As interest grows in the potentials, limits and risks of carbon dioxide removal and  
690 “natural climate solutions” including wetland restoration (Ma et al., 2024; Zou et al., 2022), it may become increasingly  
691 important to assess these fluxes with more specificity.

692

693 Overall, we find significant differences between global GHG estimates, primarily driven by the LULUCF sector, but also with  
694 non-trivial impacts from including non-Paris Agreement sources. Nonetheless, emissions are unambiguously increasing and are  
695 far off track from levels and trends consistent with meeting the objectives of the Paris Agreement. At a national level, even larger  
696 relative differences are to be expected for countries with significant land or forest areas. As it stands, though, we lack sufficient  
697 and comprehensive national data for ODS F-gases and fires to evaluate their influence below the global scale, though individual  
698 studies are starting to fill this gap (Niu et al., 2024).

699

700 A multitude of activities and processes drive GHG emissions, many of which interact with natural systems. The resulting data is  
701 therefore inherently complex, with nuances that may not be obvious to users lacking specific domain knowledge. Some issues  
702 also cannot be resolved easily, such as the attribution of synergistic effects of anthropogenic and natural drivers. Despite this,  
703 GHG emissions data is very widely used and remains one of the most important indicators of human impact on the planet.  
704 Different choices of data can have wide reaching implications, especially at a national level where varying definitions (e.g. of  
705 LULUCF emissions) could cast doubt over a country's claimed mitigation progress. We have therefore attempted to explain  
706 some of the key factors that drive differences between estimates, as well as the decision criteria underlying these choices. We  
707 recommend that data users familiarise themselves with these issues, and take steps to clearly state the decision criteria behind  
708 their own choices and what impact it may have on their analysis.  
709

710 **Data availability:** the data used in this study to make figures 9-14 is available at: <https://doi.org/10.5281/zenodo.15126539>  
711 (Lamb, 2026).

712  
713 **Code availability:** the code used in this study to make figures 9-14 is available at: [https://github.com/ClimateIndicator/GHG-](https://github.com/ClimateIndicator/GHG-Emissions-Assessment/blob/main/GHG-Emissions-Assessment-Differences-2026.Rmd)  
714 [Emissions-Assessment/blob/main/GHG-Emissions-Assessment-Differences-2026.Rmd](https://github.com/ClimateIndicator/GHG-Emissions-Assessment/blob/main/GHG-Emissions-Assessment-Differences-2026.Rmd)

715  
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727

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