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The LULUCF Data Hub: translating global land use emissions estimates into the national GHG inventory framework.

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Abstract

Global estimates of anthropogenic land use CO_2 fluxes from bookkeeping models and dynamic global vegetation models, as well as those derived from Earth observations (EO), can differ widely from those obtained by aggregation of national GHG inventories (NGHGI). These discrepancies are mostly due to conceptual differences, reflecting varying definitions (or system boundaries) of anthropogenic CO_2 fluxes, particularly on the forest carbon sink. This study presents a new online platform – the "LULUCF Data Hub" – which compiles various datasets of country-level CO_2 emissions and removals from land use, land-use change and forestry (LULUCF). Through a multi-disciplinary collaboration, results from two key global initiatives – one based on carbon cycle modelling (Global Carbon Budget, GCB 2024) and one on Earth Observations (Global Forest Watch, GFW 2024) – are "translated" to conceptually align with NGHGI definitions. We compared these global approaches to the 2024 NGHGI data submitted to the UNFCCC under the Paris Agreement reporting rules (cut-off date April 2025). The aim is to enhance comparability and foster consensus on anthropogenic land-use CO_2 flux estimates. Translating definitions between datasets considerably improves the match in land use CO_2 flux estimates, both globally and for most countries. At the global level, NGHGI indicate that LULUCF is a net sink of -3.4 Gt CO_2yr^{-1} (2001-2023 average; 2023 estimate is an extrapolation for all NGHGI), whereas GCB reports a net source of +4.7 Gt CO_2yr^{-1}. This +8.1 Gt CO_2yr^{-1} discrepancy drops

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Preprint. Discussion started: 11 February 2026

to +1.8 Gt CO_2yr^{-1} when GCB fluxes are translated to NGHGI definitions. When the global net forest-related flux of -5.8 Gt CO_2yr^{-1} estimated by the GFW model (sum of fluxes from Forest and Deforestation including organic soils) is limited to a proxy of managed forest area, the sink declines to -3.5 Gt CO_2yr^{-1}, closely aligning with NGHGI (-3.2 Gt CO_2yr^{-1} for forest-related flux only, including Forest, Deforestation, and organic soils in Indonesia). Despite improved alignment in magnitude after translation, some differences persist in global CO_2 flux trends: in the last two decades, forests (including re/afforestation) have remained a roughly constant net sink in NGHGI and GCB but are a declining net sink in GFW; deforestation emissions are stable or slightly declining in NGHGI and GCB but increase in GFW. For other land uses, NGHGI globally reports a greater sink than GCB (the GFW model does not include other land uses). At the country-level, we identify both convergences and divergences in CO_2 flux estimates between NGHGI and the translated datasets – in sign, magnitude and trend. Notably, after translation, estimates of both GCB and GFW still differ from individual NGHGI values in 19 countries by more than ±0.1 Gt CO_2 yr^{-1} on average (2001–2023), highlighting areas that deserve further investigation.

The LULUCF Data Hub was first presented in July 2024 during the IPCC Expert Meeting on Reconciling Anthropogenic Land Use Emissions, showing preliminary data. In November 2024 version 1.0 (with NGHGI pre-Paris reporting, GCB 2024 data and GFW 2024 data) was launched. Our study shows results from version 2.0, corresponding to 2024 data from all datasets: i) NGHGI data from the first Biennial Transparency Reports (BTRs) submitted under the Paris Agreement (cut-off date April 2025), complemented by previous reports (from version 1.0) for countries with no BTR submission, ii) data from GCB 2024 and iii) data from the GFW carbon flux model 2024. Data from all versions, including future annual updates, can be visualized and downloaded from the LULUCF Data Hub hosted by the European Union Forest Observatory (European Commission Joint Research Centre, 2025) and from the online repository (Melo *et al.*, 2025; available at https://doi.org/10.5281/zenodo.17140775).

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (UNFCCC, 2015) set the stage for a global effort to mitigate climate change. Science is clear that anthropogenic land-based CO_2 fluxes play a vital role in reaching the temperature goal of the Paris Agreement (IPCC, 2023) and the associated need to balance anthropogenic greenhouse gas (GHG) emissions and removals (i.e., net-zero)(Allen *et al.*, 2025). However, large discrepancies exist between land-based CO_2 fluxes reported in national GHG inventories (NGHGI) submitted by Parties to the UNFCCC and independent estimates from the global carbon modelling and Earth observation (EO) communities (Harris *et al.*, 2021; Byrne *et al.*, 2023; Grassi *et al.*, 2023; Friedlingstein *et al.*, 2025; Gibbs *et al.*, 2025). Such discrepancies contribute to confusion among policy makers about the effective role of land use, land-use change and forestry (LULUCF) in the global and national CO_2 budget and in reaching net zero GHG emissions (Grassi *et al.*, 2025; Roman-Cuesta *et al.*, 2025).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Open Access Earth System Science Data Discussions

The magnitude of these differences, the main reason for their occurrence, and their policy implications have been discussed extensively in the scientific literature (Grassi *et al.*, 2018, 2021, 2023; Schwingshackl *et al.*, 2022; Gidden *et al.*, 2023; IPCC, 2024; Allen *et al.*, 2025; Friedlingstein *et al.*, 2025; Gibbs *et al.*, 2025). The primary source of the discrepancy, especially for the forest sink, arises from the inconsistent definitions of "anthropogenic" land-based CO_2 fluxes and from the different estimation approaches (Pongratz *et al.*, 2021) used across the three communities: i) scientists supporting the development and implementation of the Intergovernmental Panel on Climate Change (IPCC) methodological guidance for NGHGI reporting, ii) global modellers contributing to the Global Carbon Budget (GCB) and the IPCC Assessment Reports, and iii) Earth observation scientists providing independent estimates.

The IPCC Guidelines for NGHGI (IPCC, 2006, 2019) are used by Parties to the UNFCCC to estimate anthropogenic GHG emissions and removals. However, for the LULUCF sector the separation of anthropogenic and natural GHG fluxes is challenging. Specifically, with the direct observations typically used in NGHGI (e.g., national forest inventories) it is not possible to attribute annual tree growth to direct human-induced effects (management practices) and exclude indirect human-induced effects such as climate change or CO_2 fertilisation. To address this methodological difficulty, the IPCC guidelines explicitly recommend that countries report emissions and removals from managed land as a proxy for anthropogenic emissions and removals. Managed land is defined in the guidelines as *land where human interventions and practices have been applied to perform production, ecological or social functions* (IPCC, 2006). Countries are required to consistently report all emissions and removals occurring in managed lands and the definition and boundaries of managed land is left to their discretion. For example, the share of managed forests is 99% in the EU27, 97% in the USA, 82% in Russia, 62% in Canada, and approximately 50% in Brazil – where it includes protected indigenous lands in the Amazonia biome.

Global carbon models used in the annual GCB assessments (Friedlingstein *et al.*, 2025) and IPCC Assessment Reports estimate CO_2 fluxes from anthropogenic land-use change (E_{LUC}) from an ensemble of bookkeeping models. These models estimate E_{LUC} by combining land-use activity data, information on carbon densities of soil and vegetation for different ecosystems, and response curves of carbon stocks after a land-use transition (e.g., decay time of litter or wood products, regrowth time of forests). With this approach, E_{LUC} includes only CO_2 fluxes directly resulting from land-use activities, such as deforestation, afforestation, logging and forest degradation (including harvest activity), shifting cultivation (cycle of cutting forest for agriculture and then abandoning), regrowth of forests (following wood harvest or agriculture abandonment), peat burning, and peat drainage (Friedlingstein *et al.*, 2025). By contrast, in the GCB, the CO_2 fluxes associated with indirect human-induced effects, in particular vegetation and soil carbon stocks responding to changes in the atmospheric CO_2 concentration and climate, are excluded from bookkeeping models. These CO_2 fluxes are considered part of the "natural", non-anthropogenic component (i.e., the natural land sink, S_{LAND}) and are estimated separately using the mean of about 20 dynamic global vegetation models (DGVMs). Consequently, a large share of the forest sink – i.e., those CO_2 fluxes associated with indirect human-induced effects – are considered anthropogenic in NGHGI but are classified as natural in the GCB. Due to this difference, global models estimate higher net anthropogenic land-use emissions than NGHGI – implying a substantial source of CO_2 to the atmosphere

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

as compared to a sink when NGHGI are summed up to global scale. The magnitude of this discrepancy amounts to about 20% of global fossil fuel CO_2 emissions (Friedlingstein *et al.*, 2025; Grassi *et al.*, 2025), and has important implications for assessing collective progress under the Paris Agreement's Global Stocktake, as it affects the remaining carbon budget (Grassi *et al.*, 2021; Gidden *et al.*, 2023) and the meaning of net-zero CO_2 for stabilizing global temperatures (Allen *et al.*, 2025). As a result, it may severely influence countries' climate ambitions (Grassi *et al.*, 2025).

In addition, since the early 2020s there has been an emergence of global net land CO_2 flux estimates from the Earth Observation research community, primarily for forests. Using atmospheric measurements (Byrne *et al.*, 2023) or satellite imagery (Harris *et al.*, 2021) that span the entire land surface, these approaches cannot distinguish between anthropogenic and natural CO_2 fluxes. Because Earth Observation based models include all forest sources and sinks (i.e., anthropogenic and natural regardless of their definition), their estimates tend to report a larger net sink compared to NGHGI. This is because in NGHGI a portion of forest area is considered "unmanaged" by some countries, and the corresponding CO_2 fluxes are not reported. This conceptual mismatch leads to substantial differences in CO_2 flux estimates at both global (Gibbs *et al.*, 2025) and country levels (Heinrich *et al.*, 2023; Deng *et al.*, 2025).

These divergences in focus and scope leading to conceptual inconsistencies in the methodological approaches and resulting estimates need to be addressed. Importantly, they can be resolved. The carbon cycle modelling (Grassi *et al.*, 2021; Schwingshackl *et al.*, 2022; Gidden *et al.*, 2023; Grassi *et al.*, 2023; Friedlingstein *et al.*, 2025) and Earth Observation (Heinrich *et al.*, 2023; Deng *et al.*, 2025; Gibbs *et al.*, 2025) communities estimating land-based CO_2 fluxes have started to align their estimates with NGHGI definitions. Furthermore, in July 2024, the IPCC Expert Meeting on Reconciling Anthropogenic Land Use Emissions convened representatives from the three communities. The meeting report (IPCC, 2024) indicated a broad agreement on the need to "translate" (a terminology that the meeting experts preferred to the alternatives "reconcile" or "harmonize") global models' estimates to the NGHGI's approach, at global and at country level, to ensure consistent information for policymaking under the UNFCCC. Such recommendations have been taken up in the outline of the IPCC 7th Assessment Report, which specifies that estimates and scenarios for anthropogenic land-based CO_2 fluxes will be consistent with national inventory definitions (Grassi *et al.*, 2025).

Given the persistent discrepancies between datasets and the growing demand from scientists and policymakers for information that is conceptually aligned, there is a clear need for platforms that facilitate transparent cross-comparisons. To support this endeavour, we introduce the Global Land Use Carbon Fluxes Data Hub (hereafter "LULUCF Data Hub"), hosted by the European Union Forest Observatory (EUFO). This platform harmonizes and visualizes country-level LULUCF data from NGHGI submissions to the UNFCCC and enables cross-comparisons with independent global land use carbon flux datasets.

This study provides an overview of the datasets available in the LULUCF Data Hub and shows annual estimates of CO_2 fluxes for the LULUCF sector from 2000 to 2023, at global and country levels, and disaggregated by land use categories. Results and figures correspond to the 2024 version of all datasets – NGHGI 2024, GCB 2024, and GFW 2024 – and to LULUCF Data Hub version 2.0. First, we show results from the update of the LULUCF NGHGI database, comprehensively described by Grassi

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

et al. (2022). Version 1.0 of the Data Hub includes the most recent database update prior to countries' transition to reporting under the Paris Agreement rules (data submitted until August 2024). Version 2.0 includes data from the first Biennial Transparency Reports (BTRs) submitted under the Paris Agreement's Enhanced Transparency Framework by 78 countries that provided data in common reporting tables (cut-off date May 2025), complemented with version 1.0 data for the remaining 107 countries. The database covers all Parties to the UNFCCC – 197 countries plus the European Union (EU27) – with 12 countries not providing LULUCF data in any submission. Second, we compare NGHGI 2024 estimates to data from the GCB 2024 (Friedlingstein *et al.*, 2025) and from the GFW carbon flux model 2024 (Gibbs *et al.*, 2025; update of Harris *et al.*, 2021), in two different steps of the translation: with fluxes reallocated to the land classes used in the NGHGI ("original/reclassified"), and in versions aligned to the NGHGI definition of anthropogenic emissions and removals ("translated"). Third, we quantify the reduction of the difference at global, regional and country levels when applying the translation methodologies to the GCB and GFW datasets, and we suggest targeted efforts to understand and reconcile the remaining differences for key regions, countries, and land classes. This initiative seeks to enhance dialogue between scientific communities, including under the Global Carbon Project (Canadell *et al.*, 2025) and the IPCC Task Force on NGHGI, and promote data transparency to support climate policy processes under the UNFCCC. The LULUCF Data Hub will continue to provide annual updates of NGHGI data as well as results from the ongoing translation efforts from the global carbon cycle modelling and global EO communities.

2 Methods

Here we describe the data displayed in the LULUCF Data Hub, the data sources, and the processing steps for a like-for-like comparison of CO_2 emissions and removals from the LULUCF sector (Figure 1). The data displayed on the LULUCF Data Hub is mostly one of synthesis and comparison of NGHGI data with estimates from carbon cycle models and the EO community. The Data Hub, as demonstrated in this study, should facilitate the comparison and access to the datasets, which are mainly described elsewhere.

Because the data are produced by different groups with different terminological preferences, we use here the terms carbon fluxes, CO_2 fluxes, or net emissions and removals interchangeably. Non-CO_2 emissions are excluded. Net CO_2 fluxes include CO_2 emissions by sources and CO_2 removals by sinks. According to the IPCC Guidelines, a source or sink is any process or activity that releases or removes, respectively, a GHG, an aerosol, or a GHG precursor into or from the atmosphere. In this study, the terms sources and sinks are often used interchangeably with emissions and removals. We use the term "LULUCF" following NGHGI (and UNFCCC) terminology, even though the GCB and GFW estimates do not strictly correspond to the LULUCF sector as defined in NGHGI reporting. Specifically, before translation, the GCB refers to CO_2 fluxes from land-use change as E_{LUC}, which does not fully correspond to LULUCF. The GFW model only includes forest-related fluxes, and therefore we neither apply the term LULUCF to GFW nor compare GFW estimates with NGHGI estimates for the total LULUCF sector. All results and figures in this study correspond to version 2.0 of the LULUCF Data Hub (2024 release).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Grassi *et al.* (2022) include a detailed description of the NGHGI database compiled by the European Commission Joint Research Centre (EC-JRC) with LULUCF data submitted by countries to the UNFCCC. Here we describe key elements of updated versions of the NGHGI database included in the LULUCF Data Hub (version 1.0 and version 2.0; section 2.1). The LULUCF Data Hub was launched in July 2024. Version 2.0, described in this study, uses NGHGI data submitted in 2024 (complemented with data from version 1.0 for countries who did not submit their first BTR by April 2025), carbon cycle model data from GCB 2024 (Friedlingstein *et al.*, 2025; see section 2.3) and EO-based data from the GFW carbon flux model 2024 (Gibbs *et al.*, 2025; see section 2.4).

Two steps are required to improve conceptual comparability between these datasets (Figure 1): "reallocation" and "alignment". We use the term "translation" when both steps are applied, as this was the term preferred by the three communities (NGHGI, global carbon cycle modellers, and Earth Observation community) during the IPCC Expert Meeting on Reconciling Anthropogenic Land-Use Emissions (IPCC, 2024; Grassi *et al.*, 2025).

In the first step, CO_2 fluxes from all data sources (NGHGI, GCB and GFW) are reallocated to the classes Forest, Deforestation, Organic Soils, HWP, and Other land uses (Table 1). NGHGI data reported in IPCC categories is reallocated to these classes in the NGHGI database to ensure greater comparability across datasets (Grassi *et al.*, 2022). The reallocation of GCB and GFW flux estimates to the NGHGI database classes has already been implemented in the most recent publications of the GCB (e.g. Friedlingstein *et al.*, 2025) and GFW (Gibbs *et al.*, 2025), marking a shift relative to the previous versions mostly focussed on "gross emissions" and "gross removals" (Friedlingstein *et al.*, 2022; Harris *et al.*, 2021). Net LULUCF is the sum of CO_2 fluxes from all five classes for NGHGI and GCB, even though E_{LUC} does not fully correspond to LULUCF (in GCB-original/reclassified). GFW includes only forest-related fluxes and is therefore never compared to the total LULUCF. Instead, we compare GFW totals to the aggregation of the NGHGI classes Forest and Deforestation (including organic soils). For the comparison of estimates of forest-related fluxes from GFW with those from NGHGI and GCB, in the latter two datasets (NGHGI and GCB), we sum the fluxes from Forest, Deforestation and Organic Soils from Indonesia because these emissions are largely associated to deforestation.

The second step aims to conceptually align the estimates of GCB and GFW to the NGHGI definition of anthropogenic CO_2 emissions and removals. Importantly, only the CO_2 fluxes allocated to the Forest class in step 1 are affected by the translation in step 2 (see sections 2.3 for GCB and 2.4 for GFW) because most of the conceptual discrepancies in the definition of anthropogenic CO_2 fluxes among datasets occur in this class. This second step has already been implemented in several publications (Schwingshackl *et al.*, 2022; Grassi *et al.*, 2023; Heinrich *et al.*, 2023; Friedlingstein *et al.*, 2025; Gibbs *et al.*, 2025). This study combines and compares all these translation efforts in the context of the LULUCF Data Hub, using the latest NGHGI data.

The alignment (step 2 of the translation, Figure 1) requires an understanding of the use of the managed land proxy by countries. Accordingly, the GCB and GFW are informed by NGHGI submissions to identify CO_2 fluxes that countries are likely to consider anthropogenic. We introduce here the "Global JRC Proxy maps of Managed and unmanaged Forest" dataset by Rossi

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Open Access Earth System Science Data Discussions

et al. (2024) (see section 2.2) that combines global and country-based spatial data on managed forest with NGHGI information to develop maps of managed and unmanaged forest, which are used in the second step of the GCB translation to NGHGI definitions. The GFW model does not use this dataset but applies a similar input and approach to delineate managed land as described by Gibbs *et al.* (2025). Because both GCB 2024 and GFW 2024 were released in 2024, country information on the use of managed land used in step 2 corresponds to that obtained from data sources in NGHGI for version 1.0 of the LULUCF Data Hub (NGHGI 2023).

The results section compares NGHGI data with the reclassified GCB and GFW data (step 1 of Figure 1) and with the translated GCB and GFW data for those classes where a translation is necessary (net LULUCF and Forest for GCB, Forest for GFW; step 2 of Figure 1). Carbon fluxes in the LULUCF Data Hub are presented as timeseries for the period 2000-2023 (Mt $CO_2 yr^{-1}$), or as averages for 2001-2023 (averages are always for 2001-2023 unless otherwise specified). Minus (-) and plus (+) signs denote net removals from and net emissions to the atmosphere, respectively. When we compare results from all datasets, minus (-) sign denotes more removals (or less emissions) and plus (+) sign denotes more emissions (or less removals).

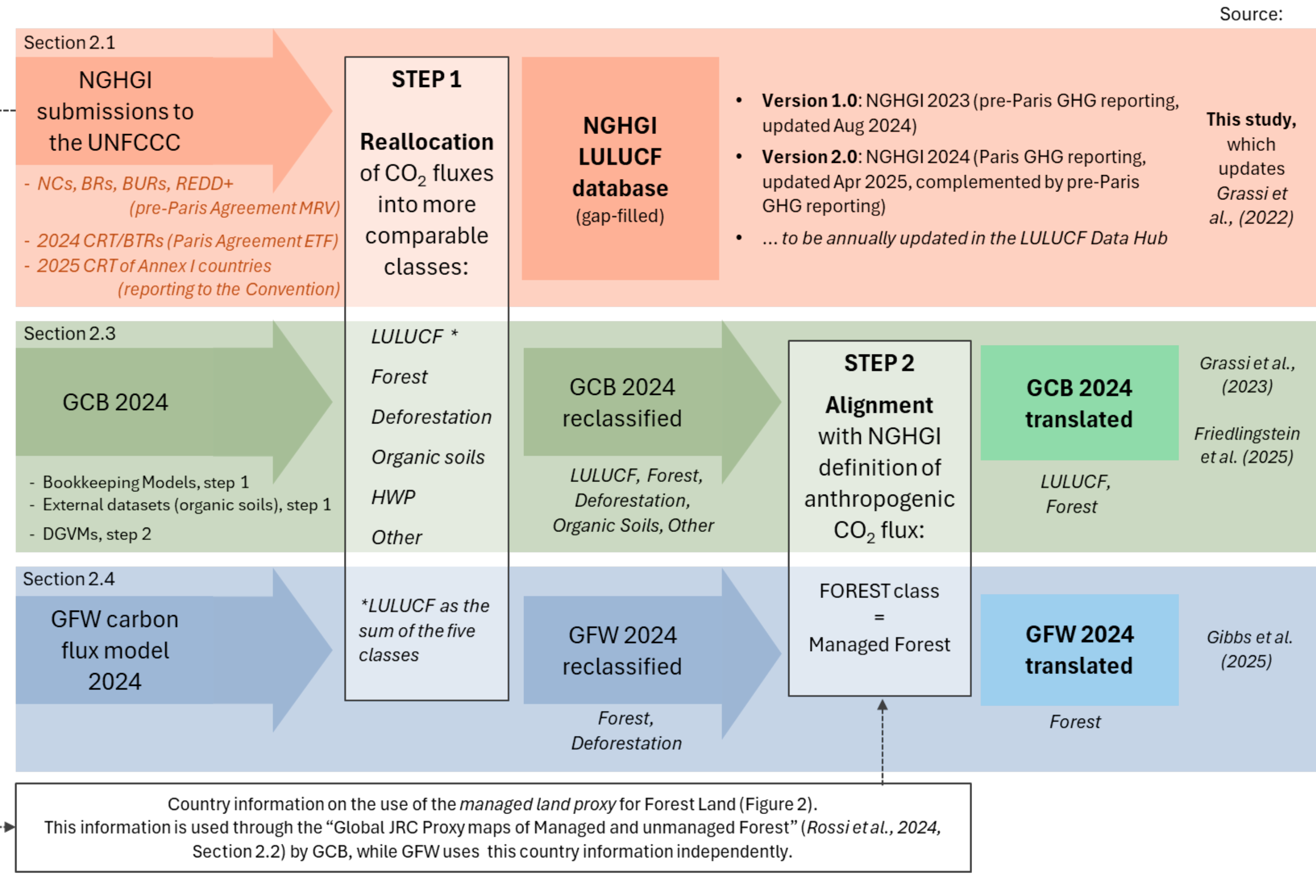

Figure 1. Illustrative flowchart of the data sources, data handling, and analysis for the reallocation and alignment of LULUCF CO_2 fluxes, collectively referred to as "translation", from the Global Carbon Budget (GCB) 2024 and Global Forest Watch (GFW) 2024 to National GHG inventories (NGHGI), to obtain the data shown in the LULUCF Data Hub (versions 1.0, 2.0). The Methods section

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

includes the following components, indicated in the top left of each processing stream: section 2.1 describes the compilation of the NGHGI LULUCF data from countries' submissions to the UNFCCC under the Measurement, Reporting and Verification framework (MRV; BR = Biennial Reports with common reporting format tables for Annex I countries, NC = National Communications and BUR = Biennial Update Reports for non-Annex I countries) and Enhanced Transparency Framework (ETF; CRT = Common Reporting Tables, BTR = Biennial Transparency Reports), and their use in Step 1 (reallocation); section 2.2 describes how NGHGI information on managed forest area is used in Step 2 (alignment); section 2.3 describes how the GCB 2024 data is translated to NGHGI definitions (based on Grassi et al. (2023) and Friedlingstein et al. (2025)); and section 2.4 describes the translation of the GFW 2024 to NGHGI definitions (based on Gibbs et al., 2025).

Table 1. Correspondence between the land-use classes used in this study and the allocation of CO_2 fluxes in national GHG inventories (NGHGI), Global Carbon Budget (GCB) and the Global Forest Watch carbon flux model (GFW). This table reflects Step 1 of the translation to NGHGI (see Figure 1), which is already implemented in GCB 2024 (see Friedlingstein *et al.* (2025) and section 2.3), and GFW (see Gibbs *et al.*, (2025) and section 2.4) where the net land-use CO_2 fluxes (E_{LUC} for GCB) and forest-related gross CO_2 emissions and removals (for GFW) are disaggregated to best match the NGHGI classes (Forest, Deforestation, Organic Soils, HWP and Other). The reallocation of CO_2 fluxes from IPCC categories in NGHGI and classes in the NGHGI database (and this study) is described by Grassi *et al.* (2022). LULUCF is the sum of CO_2 fluxes from the five classes (for NGHGI and GCB). * GFW includes emissions from organic soils in Deforestation and the GFW total for forest-related fluxes will include these emissions; for consistency, in the comparison of forest-related fluxes in this study we add emissions from organic soils in Indonesia to the fluxes from Forest and Deforestation in NGHGI and GCB.

Class in this study (and the NGHGI database)	NGHGI IPCC reporting categories and sub-categories	Global Carbon Budget (GCB) 2024	Global Forest Watch (GFW) 2024
Forest	Forest Land (FL) category, including all sub-categories of FL remaining FL and land use categories converted to FL. Excludes CO_2 fluxes from organic soils. Decay of wood products not included here, but as part of HWP.	Forest regrowth after abandonment of agricultural area or as part of forestry, wood harvest (and decay of HWPs) and other forest management, shifting agriculture.	Emissions associated with the drivers of tree cover loss: all forestry, all wildfire, and shifting agriculture only in secondary forests. All removals in the GFW carbon flux model. Decay of HWPs not included.
Deforestation	Cropland converted to FL, Grassland converted to FL, Wetlands converted to FL, Settlement converted to FL, Other Land converted to FL. Excludes CO_2 fluxes from organic soils from all conversions.	Permanent deforestation, i.e. all types of deforestation except deforestation in shifting agriculture cycles (but including first-time deforestation of primary forest for shifting agriculture).	Emissions associated with the drivers of tree cover loss: all commodity-driven deforestation, all urbanization, and shifting agriculture only in primary forests. Includes emissions from organic soils *
Organic Soils	reported in all IPCC categories and sub-categories, here allocated to a separate class	Peat drainage and peat fires	Not currently separated. Included in Deforestation *
Harvested Wood Products (HWP)	HWP is reported separately, including inputs to the HWP pool (newly harvested wood) and losses (decay of previously harvested wood)	Not separated here. Included in Forest	Included in the GFW carbon flux model; not included here

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Other	IPCC categories Cropland, Grassland, Wetlands, Settlements and Other Land. Excluding: - CO_2 fluxes from the conversion from FL to any of these categories (e.g., sub-category forest land converted to cropland). - CO_2 fluxes from organic soils	Other transitions (mainly transitions between cropland, pasture, shrubland, and natural grassland)	Not included in the GFW carbon flux model

2.1 The NGHGI LULUCF database

The LULUCF datahub is centred around NGHGI data submitted by countries to the UNFCCC. Here, we describe key elements of the NGHGI database available in the LULUCF Data Hub and present updated CO_2 fluxes from land-use for the period 2000-2023 from NGHGI communicated via a range of country reports to the UNFCCC. This reflects an update to the LULUCF NGHGI database compiled by the European Commission Joint Research Centre (EC-JRC) and comprehensively described by Grassi *et al.* (2022) showing a consolidated view on the global historical anthropogenic CO_2 fluxes from the LULUCF sector as per the IPCC 2006 guidelines (IPCC, 2006). Different versions with updates to the database are reflected in updates to the LULUCF datahub. We show results from the latest version of the NGHGI database available in the Data Hub (version 2.0) but describe below version 1.0 as well for clarity regarding updates in the Data Hub (Figure 1):

- Version 1.0: NGHGI 2023. Includes country submissions to the UNFCCC before implementation of the Paris Agreement reporting rules (hereafter "pre-Paris GHG reporting", noting that reporting under the Paris Agreement started in 2024). The sources of data include: NGHGI reported in 2023 by developed (Annex I) countries submitted in common reporting format tables; and for developing (non-Annex I) countries data is extracted from the most complete and recent submission, including national communications (NC) and Biennial Update Reports (BUR; n=124), submissions under the reduced emissions from deforestation and forest degradation framework (REDD+; n=11), or nationally determined contributions (NDC; n=7). Version 1.0 of the NGHGI database includes data submitted until August 2024 and corresponds to the NGHGI dataset in the LULUCF Data Hub version 1.0.
- Version 2.0: NGHGI 2024. Includes data from country reporting under the Paris Agreement submitted in Common Reporting Tables (CRT) as part of the first Biennial Transparency Reports (BTRs; hereafter "Paris GHG reporting") for 78 countries with submitted CRT until April 2025. These data are complemented by pre-Paris GHG reporting from version 1.0 for the remaining 107 countries with LULUCF data (12 countries do not report emissions and removals for the LULUCF sector). We note that although Parties to the Paris Agreement should have submitted their first BTR at the latest by the end of 2024, at least 23 countries have submitted CRT corresponding to the first BTR at a later stage and more are expected to continue to submit (later submissions will be included in version 2.1 and subsequent updates). Version 2.0 of the NGHGI database corresponds to LULUCF Data Hub version 2.0.

Both versions of the database are and will remain available in the Data Hub as well as subsequent updates – for example, version 3.0 will correspond to version 2.0 complemented by 2025 NGHGI submitted by Annex I countries to the UNFCCC, version 4.0 will use data from version 3.0 complemented by data from the second CRT/BTR to be submitted by the end of 2026, and so on successively every year. Here we present results corresponding to version 2.0 (NGHGI reported in 2024) because it is a more complete and recent dataset from countries submissions to the UNFCCC compared to version 1.0 and a better comparison with GCB and GFW in their 2024 versions (Friedlingstein *et al.*, 2025; Gibbs *et al.*, 2025).

From the 198 Parties to the UNFCCC, the NGHGI database includes CO_2 fluxes from LULUCF for 185 countries covering almost 100% of the World's managed forests (Table 2), plus the European Union (EU27). Twelve countries do not report to the UNFCCC or do not include data for the LULUCF sector. Developed (or Annex I) countries report a complete time series 1990-2022 (which we extrapolate to 2023). However, for most developing (or non-Annex I) countries, gaps are filled through linear interpolation between the reported data points and/or through backward (to 2000) and forward (to 2023) extrapolations using the single closest available data (as described in Grassi et al. 2022). The gap-filling percentage is 43% for version 1.0 and 39% for version 2.0, in both cases lower compared to the 48% of previous published versions of the NGHGI database (Grassi *et al.*, 2022, 2023). This indicates an increasingly complete timeseries of NGHGI from developing countries. Countries where the biggest fluxes occur generally report relatively complete time series (e.g., Brazil, DRC, Indonesia, Malaysia, Nigeria, Venezuela) and most of the gap-filling was done to the data from developing countries with lower fluxes. A notable exception is China with data only for 2005, 2020 and 2021. Gap-filling and extrapolation are documented for each country and version of the database in the notes of the info sheet on the Data Hub and in supplementary data.

To facilitate the comparison of NGHGI with independent datasets, we reallocated CO_2 fluxes from reported IPCC categories and sub-categories in the NGHGI to the classes used in this study (Step 1 in Figure 1; Table 1). Accordingly, CO_2 from LULUCF (for which 95% of countries have data, Table 3) reported in IPCC land use categories (Forest Land, Cropland, Grassland, Wetlands, Settlement, Other Land) and sub-categories (e.g., 'forest land remaining forest land', 'land converted to forest land', 'cropland remaining cropland', 'forest land converted to cropland') are allocated to the classes Forest (available for 93% of country-Parties), Deforestation (available for 86% of countries), Organic soils (available for 23% of countries), Harvested wood products (HWP; 33% of countries), and Other land uses (available for 57% of countries) as explained in Table 1. Unlike previous versions of the database, here we provide HWP fluxes separately, and have improved disaggregation of LULUCF CO_2 fluxes for the classes Deforestation and Other. These improvements were enabled in version 1.0 due to the increased submission of BURs with more detailed data by developing countries in recent years – 52 countries submitted their first BUR since 2020, and 85% of the data included in version 1.0 were submitted since 2020 – and in version 2.0 due to the relatively large number of more detailed and complete submissions by developing countries – 78 countries provided tabled data in CRT format, including 35 developing countries (Table 2).

On the allocation of fluxes to classes, some assumptions were needed when using data from pre-Paris GHG reporting (58% of the countries). Emissions from forest conversion (or deforestation) are reported in the NGHGI in the post-deforestation IPCC

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

land use category. When information was not available by sub-categories (n=14 in version 2.0), it was not possible to know the share of emissions in each land use category corresponding to deforestation. For example, if net emissions were reported only aggregated for Cropland (IPCC category), it was not possible to separate the share of emissions from cropland remaining cropland, forest land converted to cropland, or any other land use categories converted to cropland. In these cases, we allocated CO_2 fluxes reported in the categories Cropland, Grassland, Wetland, Settlement, and Other Land to our class Deforestation if the country reported net emissions in those categories and to our class Other land uses if the country reported net removals in those categories. When data is available disaggregated by IPCC sub-category only for one year of the time series and aggregated by category for the remaining years, we assume the same disaggregation for all years of the timeseries. All assumptions for allocation of CO_2 fluxes to our land use classes for each country and version of the database are available in the notes of the info sheet on the Data Hub and in supplementary data.

Table 2: Sources of country LULUCF data reported to the UNFCCC split by developed (Annex I) and developing (non-Annex I) countries used in version 2.0 of the NGHGI database and split by regional groupings (classification adopted in the IPCC AR6 WGIII, IPCC (2022)). Possible sources are Common Reporting Tables submitted with the first Biennial Transparency Reports due in 2024 (CRT/BTR 2024; "Paris GHG reporting"), National Communications (NC), Biennial Update Reports (BUR) submitted to the UNFCCC before implementation of the Paris Agreement reporting rules ("pre-Paris GHG reporting"), submissions to the REDD+ framework, and National Determined Contributions (NDC). Forest area estimates (total and managed) are for the reference year 2020 for developed countries and for most developing countries that reported areas in the common reporting tables (CRT/BTR 2024), while we use the average for the period 2010-2020 for the remaining developing countries. For the latter group of countries, total forest areas are indicative, as they are extracted from country reports and have different sources; in case of lack of information

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Open Access Earth System Science Data Discussions

the total forest area reported to the FAO FRA was used, assuming all forest as managed. Managed forest areas, when different from total forest area, are always explicitly indicated in country reports (n=9 countries).

Party/Region group	Source used	No. of countries	Forest area: Total		Forest area: Managed		Share of managed forest
			Mha	%	Mha	%	%
Developed (Annex I)	CRT/BTR 2024	43	1,969	44%	1,661	45%	84%
Developing (non-Annex I)	CRT/BTR 2024	35	1,275	29%	963	26%	74%
	NC/BUR	92	1,036	23%	963	26%	93%
	REDD+	10	119	3%	91	2%	76%
	NDC	5	34	1%	34	1%	100%
	No LULUCF data	12	4	0.1%			
Total		**197**	**4,436**		**3,715**		**84%**
Africa		54	767	17%	738	20%	96%
	CRT/BTR 2024	10	124	3%	124	3%	100%
	Pre-Paris reporting	41	640	14%	612	16%	96%
	No LULUCF data	3	3	0%	0	0%	100%
Asia and developed Pacific		3	172	4%	172	5%	100%
	CRT/BTR 2024	3	172	4%	172	5%	100%
Eastern Asia		4	333	8%	333	9%	100%
	CRT/BTR 2024	1	304	7%	304	8%	100%
	Pre-Paris reporting	3	30	1%	30	1%	100%
Eastern Europe and West-Central Asia		12	939	21%	779	21%	83%
	CRT/BTR 2024	8	930	21%	773	21%	83%
	Pre-Paris reporting	4	6	0%	6	0%	100%
Europe		42	225	5%	222	6%	99%
	CRT/BTR 2024	36	221	5%	219	6%	99%
	Pre-Paris reporting	5	4	0%	4	0%	100%
	No LULUCF data	1					
Latin America and Caribbean		31	988	22%	604	16%	61%
	CRT/BTR 2024	12	722	16%	410	11%	57%
	Pre-Paris reporting	19	266	6%	194	5%	73%
Middle East		14	18	0%	17	0%	95%
	CRT/BTR 2024	1	0	0%	0	0%	100%
	Pre-Paris reporting	9	17	0%	16	0%	94%
	No LULUCF data	4	1	0%	1	0%	100%
North America		2	653	15%	507	14%	78%
	CRT/BTR 2024	2	653	15%	507	14%	78%
South-East Asia and developing Pacific		27	253	6%	253	7%	100%
	CRT/BTR 2024	4	113	3%	113	3%	100%
	Pre-Paris reporting	20	140	3%	140	4%	100%
	No LULUCF data	3	0	0%	0	0%	100%
Southern Asia		8	90	2%	90	2%	100%
	CRT/BTR 2024	1	3	0%	3	0%	100%
	Pre-Paris reporting	6	87	2%	87	2%	100%
	No LULUCF data	1	0	0%	0	0%	100%

Table 3: Land use categories reported in NGHGI and used in this study. Indicated are the number of countries (n) and the share of countries (%) reporting data for the categories LULUCF, Forest, Deforestation, Organic soils, HWP, and Other. Data split by

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

UNFCCC grouping of developed (Annex I) and developing (non-Annex I) countries and by regional groupings following the classification adopted in the IPCC AR6 WGIII, (IPCC 2022).

			LULUCF		Forest		Deforestation		Org. soils		HWP		Other	
		No. of countries	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)
	World	197	185	(95%)	182	(93%)	168	(86%)	44	(23%)	65	(33%)	112	(57%)
	Developed countries (Annex I)	43	43	(100%)	43	(100%)	40	(93%)	35	(81%)	39	(91%)	42	(98%)
	Developing countries (non Annex I)	154	142	(93%)	139	(91%)	128	(84%)	9	(6%)	26	(17%)	70	(46%)
Regional groupings	Africa	54	51	(91%)	48	(86%)	47	(84%)	0	(0%)	10	(18%)	26	(46%)
	Asia and developed Pacific	3	3	(100%)	3	(100%)	3	(100%)	3	(100%)	3	(100%)	3	(100%)
	Eastern Asia	4	4	(100%)	4	(100%)	4	(100%)	0	(0%)	2	(50%)	3	(75%)
	Eastern Europe and West-Central Asia	12	12	(100%)	12	(100%)	6	(50%)	3	(25%)	3	(25%)	9	(75%)
	Europe	42	41	(100%)	41	(100%)	38	(93%)	28	(68%)	34	(83%)	36	(88%)
	Latin America and Caribbean	31	31	(100%)	31	(100%)	31	(100%)	3	(10%)	10	(32%)	19	(61%)
	Middle East	14	10	(91%)	10	(91%)	9	(82%)	0	(0%)	0	(0%)	2	(18%)
	North America	2	2	(100%)	2	(100%)	2	(100%)	2	(100%)	2	(100%)	2	(100%)
	South-East Asia and developing Pacific	27	24	(89%)	24	(89%)	21	(78%)	5	(19%)	1	(4%)	8	(30%)
	Southern Asia	8	7	(88%)	7	(88%)	7	(88%)	0	(0%)	0	(0%)	4	(50%)

The definition of managed land at the country level is essential for the global modelling and Earth observation communities for translating their data into a conceptually similar framework as NGHGI (step 2 of Figure 1). Therefore, for each country, we also document in the information sheet panel of the LULUCF Data Hub and as csv file (supplementary) information on the use of the IPCC managed land concept as a proxy for anthropogenic land-based CO_2 fluxes (IPCC, 2006, 2019), and information on the extent to which CO_2 removals in managed forest are included in the NGHGI. Political decisions may determine that a country reports all forest area as managed forest but for some reason does not include all sinks. For example, there are cases of incompleteness in reporting due to lack of accurate data on annual tree growth, examples of countries where carbon removals from tree growth is only included in plantation areas, or on secondary forests, or only on protected areas. Therefore, in addition to the information on total forest area and the share of managed forest area found in CRT and in tables or texts from NC or BUR (Table 2), we documented country decisions on whether and how the managed land proxy was applied. We grouped countries according to their explicit or implicit use of the managed land proxy (Figure 2A) and according to the completeness of reporting of CO_2 removals in the forest land category (Figure 2B). Part A of the decision tree informs the development of the Managed Forest maps (described in section 2.2) and is used in Step 2 for translation of the GCB and GFW estimates (Figure 1). Part B explaining why differences in the estimates remain in some countries and occasionally may be used to make expert judgement decisions on the Managed Forest maps. Specifically, if all land is explicitly managed but CO_2 removals are not fully included in all forest land (e.g., Colombia and Ecuador in A1B3), these countries may be allocated to group A4 in the alignment step (Step 2, Figure 1) (for example, see below in section 2.2 and the country allocation in Gibbs *et al.* (2025).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

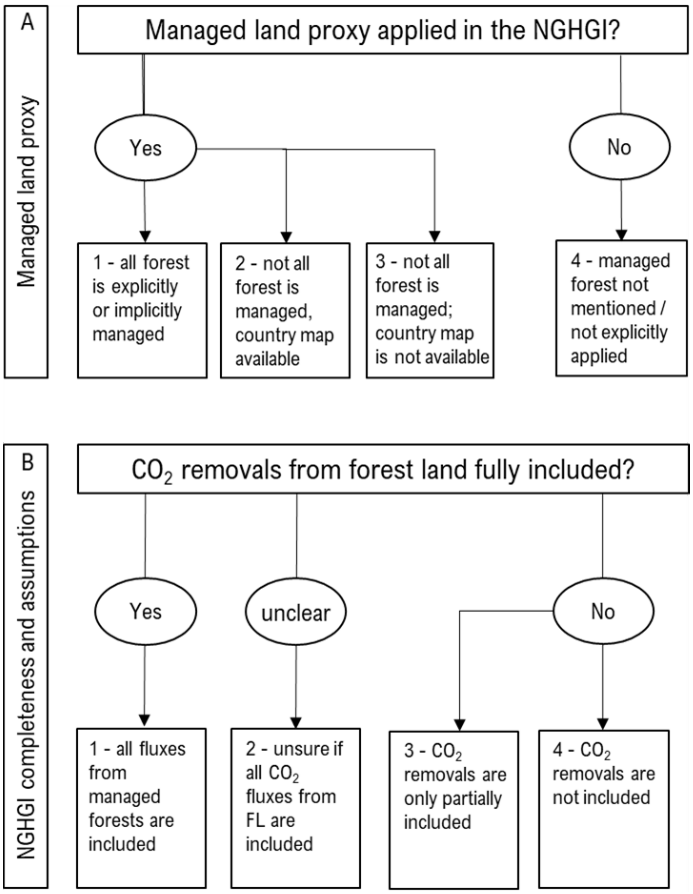

Figure 2: Decision tree with information on a) the explicit use of the managed land proxy by country-Parties in their national GHG inventories (NGHGI) used in Step 2 of the translation of datasets (Figure 1), and b) the extent to which CO_2 removals in Forest Land (FL) are included in the NGHGI, to understand why differences in the estimates may remain after translation.

2.2 The Managed Forest map 2024

The "Global JRC Proxy maps of Managed and unmanaged Forest" (Rossi *et al.*, 2024) was developed to support the disaggregation of global, geospatial datasets into anthropogenic and natural fluxes as defined by countries' NGHGI using the IPCC guidelines. It is a publicly available and regularly updated spatially explicit dataset that uses global Earth observation-derived data and country-based geospatial polygons of managed forest areas to generate maps of managed forests at a spatial resolution of 5- and 50-kilometers for different years (2000, 2010, and 2020). The dataset and its technical documentation can be accessed here: https://zenodo.org/records/14549036.

The maps are generated in three steps. The first step combined maps of fractional tree cover for the year 2000 and of annual forest loss from the Global Forest Change (GFC) dataset (Hansen *et al.*, 2013) with tree cover gain (2000-2012) from GFC complemented with tree cover gain 2000-2020 from Potapov *et al.* (2022). In the second step, the maps of tree cover dynamics are filtered at the country level by selecting country-appropriate tree cover thresholds based on information reported by

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

countries to the FAO Forest Resource Assessment (FRA) (FAO, 2020). The approach selected was to define the tree cover threshold (varying between 10% and 80%) that minimizes the difference between the forest area obtained in the combined maps and the total forest area statistics as reported by countries to the FAO FRA 2020, individually for each country – see a table with the selected thresholds and share of managed forest by country in Rossi *et al.* (2024). For all countries, the minimum area that defines forest was set at 0.5 hectares (Rossi *et al.*, 2024).

The final step varies for each group of countries identified in the decision tree (Figure 2, panel A 1-4) grouping countries according to their use of the IPCC "managed land" concept as proxy for anthropogenic land-based CO_2 fluxes (IPCC 2006, 2019) and on the availability (and accessibility) of national geospatial layers delineating managed forest areas. Countries in group A1 (n=41, including all EU member states, China, India and Indonesia) explicitly or implicitly consider all forest managed, and therefore no additional processing is required. For countries in group A2 (Brazil, Canada and USA) the maps of managed land used in NGHGI are intersected with the forest maps from step 1 (Brazil) or the national managed forest maps are used directly (Canada). Finally, for countries in group A3 (Russia) and in group A4 (most developing countries), maps of intact forest landscapes maps (Potapov et al., 2017) are combined with the forest maps obtained in the first step as an approximation of unmanaged forests. Managed forests are all forests not identified as unmanaged. Specifically, the intact forest layers are available for 2000, 2013 and 2020, and were used for 2000, 2010, and 2020, respectively. Expert judgment is implemented based on information from country reports (and in Figure 2, panel B 1-4) in cases a country explicitly considers all land as managed land for political reasons but for technical reasons does not include CO_2 removals from all managed forest (cases A1B3-4 Figure 2).

The "Global JRC Proxy maps of Managed and unmanaged Forest" dataset was used to add the indirect anthropogenic effects estimated by DGVMs (e.g., due to increased atmospheric CO_2) to the original GCB land-use fluxes (E_{LUC}) (see section 2.3).

2.3 The Global Carbon Budget 2024 translation to NGHGI definitions

The LULUCF datahub versions 1.0 and 2.0 use data from GCB 2024 (Friedlingstein *et al.*, 2025) (Figure 1). The GCB dataset uses a combination of two separate model approaches to simulate terrestrial CO_2 fluxes: (1) four bookkeeping models – BLUE (Hansis *et al.*, 2015), OSCAR (Gasser *et al.*, 2020), H&C2023 (Houghton and Castanho, 2023) and LUCE (Qin *et al.*, 2024) – to estimate the anthropogenic land-use CO_2 fluxes (E_{LUC}), and (2) an ensemble of DGVMs to estimate the natural land sink component (S_{LAND}).

Following the translation steps outlined in Figure 1, the net land-use fluxes (E_{LUC}) are first sub-divided into sub-components of CO_2 fluxes from: permanent deforestation, forest regrowth, shifting cultivation, wood harvest and other forest management, peat drainage and peat fires (from external datasets to the bookkeeping models) and all other transitions (Friedlingstein *et al.*, 2025). Although in the reallocation step of the translation the sub-components from the GCB are allocated in the best possible way to the classes used in the LULUCF Data Hub (Table 1; and as described by Grassi *et al.*, 2023), some discrepancies still remain. For example, in the GCB the release of CO_2 from the decay of harvested wood is included in the wood harvest sub-

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

component (aggregated under Forest in this study, Table 1), whereas the NGHGI dataset, in line with the IPCC guidelines, includes a Harvested Wood Products class which reflects the evolution of carbon stocks in the harvest wood product pool, affected annually by gains (new wood products entering the pool) and losses (decay of previously harvested wood) – with negative HWP CO_2 fluxes indicating gains greater than losses. In this case, the best comparison would be between Forest in GCB and Forest+HWP in NGHGI. However, given the relatively small contribution of HWP in NGHGI, this remaining mismatch in system boundaries will be addressed in future versions of the LULUCF Data Hub.

The country-level GCB net CO_2 fluxes between 2000 and 2023, reallocated as describe above, are hereafter referred to as "Global Carbon Budget (GCB) 2024 original/reclassified" (results of step 1 in Figure 1). Information on data quality of bookkeeping models' results for individual countries (quality flags) can be found in the data supplement to GCB 2024 (GCP, 2024; Friedlingstein *et al.*, 2025).

GCB 2024 original/reclassified includes in the Forest class the net fluxes from forest regrowth (re-/afforestation), from wood harvesting and other forest management, and from shifting agriculture cycles (Table 1). The next step in the translation of GCB 2024 to NGHGI definitions (Step 2 in Figure 1) requires adding the 'natural' land sink (S_{LAND}) on managed forests from 17 dynamic global vegetation models (DGVMs, whose number slightly varies in different GCB versions) to the net CO_2 flux of the Forest class from bookkeeping models, as described by Grassi *et al.* (2023) and implemented by Friedlingstein *et al.* (2025). Unlike those two studies, here the estimated area of countries' managed forest used to filter the DGVMs results considers the temporal dynamics (i.e., maps for the years 2000, 2010 and 2020) as described by Rossi *et al.* (2024; see section 2.2 above). Adding the large CO_2 sink caused by indirectly human-induced environmental change in countries' managed forests (estimated by the DGVMs) to the directly human-induced land-use CO_2 flux from the four bookkeeping models results in estimates for the Forest class that are conceptually more comparable to NGHGI because they include direct and indirect anthropogenic effects. The results from this step (for Forest and LULUCF classes) is hereafter referred to as "Global Carbon Budget (GCB) 2024 translated".

2.4 The Global Forest Watch 2024 translation to NGHGI definitions

The Global Forest Watch carbon flux model (GFW model) provides globally consistent, independent and regularly updated open-access maps of forest carbon fluxes from 2001 onwards through the integration of satellite-derived maps and other geospatial products. The GFW model combines global forest change maps (forest defined as tree canopy density >30%; Hansen *et al.*, 2013), benchmark carbon density maps, and other Earth observation-derived data to estimate forest-related GHG emissions and removals following the IPCC default gain-loss method (IPCC 2006, 2019). Removals from standing tree cover and tree cover gain are reported as an annual average across the entire model period (for this analysis, 2001-2023) instead of annually for areas of forest remaining forest and non-forest converted to forest. Emissions from tree cover loss are reported annually, in the year in which the tree cover loss was detected (as "committed emissions" or "instantaneous oxidation", meaning that all subsequent emissions from biomass, deadwood and litter carbon are attributed to the year of tree cover loss).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Furthermore, the GFW model includes emissions from organic soil if it coincides with tree cover loss or loss of and planted forests (Richter *et al.*, 2024). The GFW model is comprehensively described by Harris *et al.* (2021).

In the original version of the GFW model (Harris *et al.,* 2021), all "observed" GHG fluxes were modeled without attempting to split between anthropogenic and natural sources. Gibbs *et al.* (2025) described recent updates to the GFW model and introduced the post-hoc translation of GFW's CO_2 fluxes to NGHGI definitions of anthropogenic and natural. This translated output is shown in the LULUCF Data Hub and offers a Earth Observation perspective on forest-related fluxes for comparison with NGHGI. To obtain conceptually similar estimates, two processing steps were applied by Gibbs *et al.* (2025) (Figure 1): the first step addresses differences in reporting categories and the second one addresses the delineation between anthropogenic and natural fluxes.

For the first step of assigning fluxes to reporting categories (reallocation, step 1 in Figure 1), Gibbs *et al.* intersected gross CO_2 emissions and removals from the GFW model with a map of the dominant drivers of tree cover loss (Curtis *et al.*, 2018; updated through 2023). With some exceptions described in Gibbs *et al.* (2025), the total CO_2 fluxes in the model were partitioned between the classes i) Forest, if the driver of tree cover loss was identified as forestry, wildfire or shifting agriculture in secondary forests, and ii) Deforestation if the driver of tree cover loss was commodity-driven deforestation, urbanization, and shifting agriculture in primary forests (Table 1). Consistent with the NGHGI database, the decay of harvested wood products is not included in the Forest class (Table 1). Due to current limitations in the disaggregation of the GFW model, emissions from organic soils are included in the Deforestation class. This processing step resulted in CO_2 emissions and removals from the GFW model being reallocated to the two classes Forest and Deforestation (Table 1). In this study we refer to it hereafter as "Global Forest Watch (GFW) 2024 original/reclassified".

GFW 2024 original/reclassified does not differentiate between anthropogenic and non-anthropogenic forest-related CO_2 fluxes. To increase the conceptual similarity between the GFW model and NGHGI, Gibbs *et al.* took the second step of applying available information on the use of the managed land proxy by countries in their NGHGI (decision tree in Figure 2A) to determine the forest areas considered managed and identify the corresponding CO_2 fluxes that countries are likely to consider anthropogenic. The Managed Forest map dataset (Rossi *et al.*, 2024; section 2.2) was not used as in the GCB translation (section 2.3) but Gibbs *et al.* (2025) applies a similar input and approach to delineate managed land. Countries were grouped as follows: (1) countries that consider all forest land as managed (A1 in Figure 2), (2) countries that apply the managed land proxy and provide a map of managed land (A2), and (3) countries that that do not provide a map or for which it remains unclear whether they apply the managed land proxy (A3 and A4 respectively). For countries in groups A3 and A4 (n=143), maps of humid tropical forests (Turubanova *et al.*, 2018) and of intact forest landscapes (Potapov *et al.*, 2017) were used as an approximation of unmanaged forests in tropical and extratropical regions, respectively. All other forests were considered managed, and therefore all those fluxes were considered anthropogenic. For all countries, the drivers of tree cover loss (Curtis *et al.*, 2018) were used to further adjust the maps of unmanaged forests. For example, if an area mapped as unmanaged forest had tree cover loss with the driver of commodity-driven deforestation, then the area was reassigned to managed forest and

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

emissions allocated to the class deforestation. The grouping of countries was the same as used in the translation of the GCB data (both based on information as shown in the decision tree of Figure 2) but the boundaries may differ because different maps were used as an approximation of unmanaged forests for countries in groups A3 (Russia) and A4 (most developing countries). Following the implementation of this second step to exclude non-anthropogenic CO_2 fluxes through the approximation of unmanaged forests, the annual CO_2 fluxes from the Forest class in GFW 2024 original/reclassified include only CO_2 fluxes in managed forests and are referred to hereafter as "Global Forest Watch (GFW) 2024 translated".

2.5 The global land-use carbon fluxes (LULUCF Data Hub) in the EU Forest Observatory

The Global Land-Use Carbon Fluxes Data Hub (or LULUCF Data Hub) is a component of the EU Forest Observatory (EUFO). The EUFO was established and is maintained by the European Commission Joint Research Centre (EC-JRC) with the objective of facilitating access to information on supply chains for public entities, consumers and businesses (JRC, 2023). The LULUCF Data Hub provides downloadable country-level CO_2 flux data from the NGHGI database compiling LULUCF data submitted by countries to the UNFCCC and the Paris Agreement along with country information sheets detailing the data sources, and important reporting choices and assumptions. It also compares NGHGI estimates with global land-use CO_2 flux datasets translated to NGHGI definitions (in step 1 and step 2 in Figure 1). All datasets displayed in the LULUCF datahub can be downloaded in the EUFO by country or in a single bulk download in the online repository (Melo *et al.*, 2025a).

The data and methods described in this study correspond to versions 1.0 and 2.0 of the LULUCF Data Hub, but the results and figures shown here correspond to version 2.0. The LULUCF Data Hub will be updated annually, and all versions will remain available in the EU Forest Observatory to illustrate how the NGHGI database and other datasets evolve over time. Additional comparison datasets are expected to be included in the future if they attain: i) conceptual alignment with NGHGI, and ii) global coverage with country-level estimates. Furthermore, they must iii) be scientifically rigorous with documentation available in peer-reviewed journals, iv) be operational or regularly updated, either by being part of an established initiative or through endorsement by a recognized organization or institution, and v) provide open access code and data.

2.6 Uncertainties

Estimating CO_2 fluxes from the LULUCF sector is challenging, due to their high spatial and temporal variability. As a result, land use is the most uncertain category in the global carbon cycle (Friedlingstein *et al.*, 2025). These large uncertainties have contributed to the omission of flux estimates from LULUCF from global assessments (e.g. the first Global Stocktake, Roman-Cuesta *et al.,* 2025). Methodological choices, data completeness and quality, and the level of aggregation affect the uncertainty estimation of LULUCF net emission/removal and trends. Since the various datasets illustrated in this study use different approaches to estimate and report uncertainties, we do not explicitly compare uncertainty values across datasets. Nevertheless, we report below some information from the different datasets. A more comprehensive discussion of the underlying reasons for

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

the uncertainties of the CO_2 flux estimates in the land use sector, including differences across datasets, can be found in Pongratz *et al.* (2021) and (Obermeier *et al.*, *in press*).

In accordance with the IPCC Guidelines (IPCC, 2006, 2019), estimates in NGHGI should be accurate in the sense that they are neither systematically over- nor under-estimating the true emissions or removals, so far as can be judged, and they should be precise so far as practicable. In the context of NGHGI, the qualitative and quantitative understanding of uncertainty in individual estimates and overall totals is aimed to help prioritizing methodological and data collection improvements within a specific NGHGI, and not necessarily to be compared with other NGHGI or different datasets.

NGHGIs express the uncertainty as 95% confidence interval. Based on the available information – which is not complete for all countries – the overall uncertainty of net LULUCF flux is estimated as ~35% for Annex I Parties (dominated by the forest sink) and ~50% for Non-Annex I Parties (dominated by deforestation emissions) (Grassi *et al.*, 2022), although large variations exist among countries. Similar values are reported by Roman-Cuesta *et al.* (2025), using also data from McGlynn *et al.* (2022). The models used in the Global Carbon Budget express the uncertainty as +/-1 standard deviation, estimated across four bookkeeping models and approximately 20 DGVMs (Friedlingstein *et al.*, 2025). The GFW model estimates uncertainty (+/-1 standard deviation) using IPCC formulae for propagation of errors in key inputs to the model (Gibbs *et al.*, 2025); uncertainty is estimated for gross emissions, gross removals, and net flux both globally and by climate domain.

Incorporating the uncertainties from different datasets, which are all calculated differently, is a challenging task. Furthermore, using traditional methods to calculate the uncertainty (e.g. standard error or standard deviation) when uncertainties are sometimes well over 50% (especially if gross emissions and gross removals nearly compensate, and the net flux is very close to zero), or have biases not included in the uncertainty analysis, may not be the best approach. Instead, relying on the convergence of evidence, after translations, as we have done here, may be a more helpful contribution to highlight where remaining work is needed.

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

3 Results and discussion

3.1 Updates to the LULUCF NGHGI database

The LULUCF NGHGI database 2024 indicates a net mean global flux from LULUCF of -3.4 Gt CO_2yr^{-1} over 2001–2023. This net removal is largely driven by a Forest sink of -7.3 Gt CO_2yr^{-1} and a Deforestation source of +3.6 Gt CO_2yr^{-1}. Additional smaller land fluxes such as emissions from Organic soils (+0.8 Gt CO_2yr^{-1}), removals from Other land categories (-0.3 Gt CO_2yr^{-1}) and HWP contribution (-0.2 Gt CO_2yr^{-1}) largely balance each other (Figure 3a). Forest-related net fluxes amount to -3.2 Gt CO_2yr^{-1} over 2001–2023 and include the sum of fluxes of Forest and Deforestation, plus emissions from organic soils in Indonesia for consistency and comparison with other datasets. A slight trend of decreasing CO_2 emissions from deforestation and increasing CO_2 removals from forests and other land uses in developing countries contrasts with no trend in deforestation and a decrease in the forest sink in recent years in developed countries (Figure 3b).

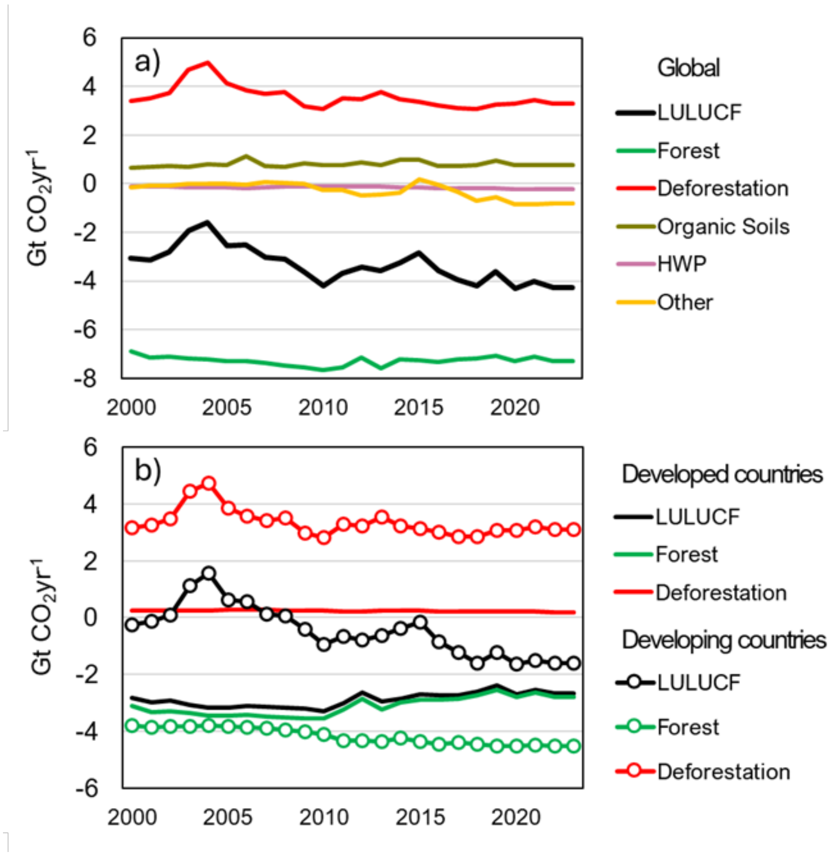

Figure 3: Global time series (2000–2023) of CO_2 fluxes from the LULUCF NGHGI database by (a) land-use class, and (b) split between UNFCCC developed (Annex I) and developing (non-Annex I) countries for LULUCF, Forest and Deforestation. Data for the year 2023 is extrapolated in all NGHGI.

The estimates of the NGHGI database have been changing over time, as countries may update and recalculate their estimates with each NGHGI (Figure 4; in Grassi *et al.*, 2017, 2018, 2021, 2022, 2023 and the current versions in the LULUCF Data Hub

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

– versions 1.0 and 2.0). In 2018, when Grassi *et al.* (2018) used an initial version of the NGHGI database to quantify the gap in land CO_2 fluxes between the aggregation of NGHGI and global models for the first time, the LULUCF sector globally was a decreasing net source of +0.1 Gt CO_2yr^{-1} (for 2005-2015; light blue line in Figure 4). For the same period (2005-2015), the version of the database discussed here (2.0) quantifies the LULUCF sector as a net sink of -3.3 Gt CO_2yr^{-1}. From version 1.0 to version 2.0, the reported net LULUCF removals from developed (Annex I) countries increased by 0.9 Gt CO_2yr^{-1} (2001-2023 average) due to recalculations in some NGHGI (Figure 4b). The biggest contributor to this recalculation was Russia, whose forest sink substantially increased mostly due to new forest inventory data (Russian Federation, 2024). However, for most of the previous updates, NGHGI from developed countries have been stable and most of the shift occurred in developing (non-Annex I) countries' reporting (Figure 4c). The current NGHGI update (version 2.0, red line in Figure 4) shows a larger net sink reported by developing countries compared to previous versions of the database, with LULUCF shifting from a net source of 2.0 Gt CO_2yr^{-1} in Grassi *et al.* (2018) to a net sink of -0.2 Gt CO_2yr^{-1} (average 2005-2015). In this case, the shift reflects the increased reporting capabilities of developing countries in recent years, i.e. more countries reporting and more complete reporting. Historically, reporting under the UNFCCC was always more stringent for developed countries (with annual reporting requirements). With such stringency came also a legacy of continual improvements and capacity on repeated national forest inventory measurements, forest monitoring, GHG compilation, reporting and verification. At the time of Grassi *et al.* (2018), all developed (Annex I) countries had submitted their annual NGHGI with complete timeseries, while only 26% (n=40) of developing countries had submitted at least one BUR. Therefore, at that time, the database was rather incomplete for developing countries. In version 2.0 (NGHGI 2024) of the database, 25% (n=35) of developing countries have submitted data in tabular format under the Enhanced Transparency Framework (ETF, i.e., Biennial Transparency Reports under the Paris Agreement) following the same reporting rules as developed countries, and 80% (n=113) have submitted at least one BUR. We expect that the NGHGI database will continue to reflect the development of NGHGI capacity in developing countries in the future, as more countries transition to the ETF rules. This evolution will be seen in the LULUCF Data Hub which will keep all versions of the database available for visualisation and download.

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

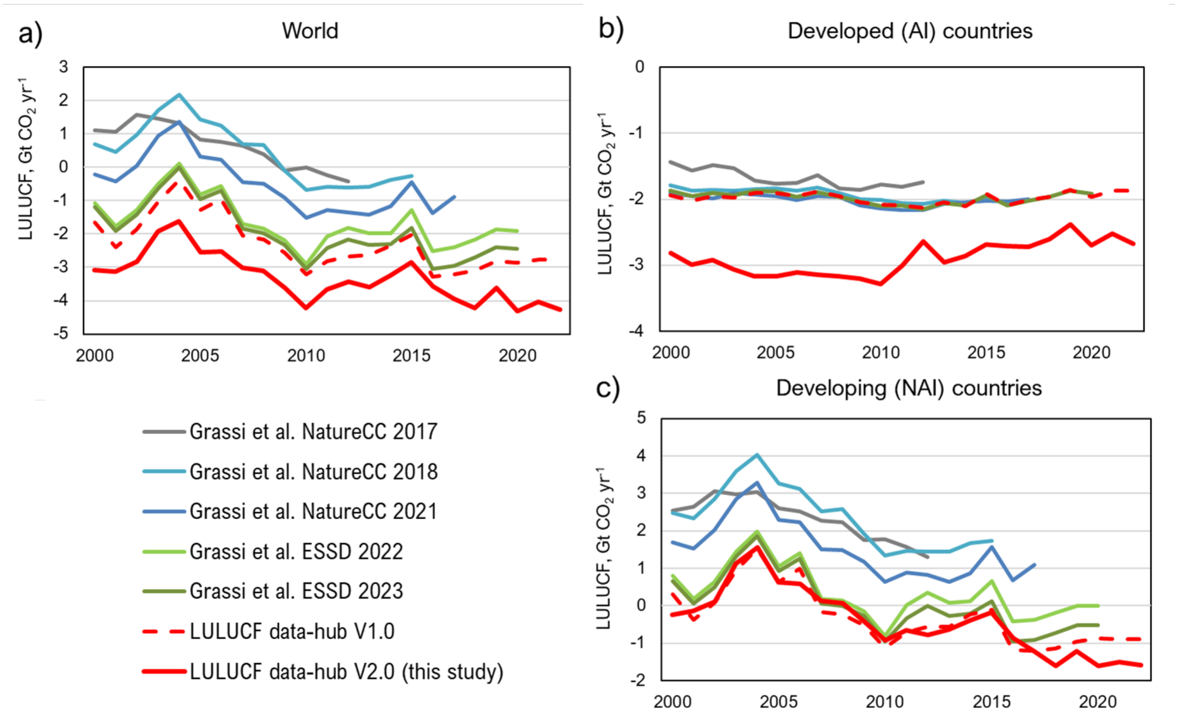

Figure 4: Timeseries of CO_2 fluxes in 2000–2023 from the NGHGI LULUCF database used in peer-reviewed articles since 2017 and up to this current study (a), split between developed (b) and developing (c) country-Parties to the UNFCCC.

A map of the annual average CO_2 fluxes from LULUCF by country (Figure 5) highlights how countries with the largest net removals (China, Russia, USA, India) and largest net emissions (Brazil, Indonesia, Nigeria, Democratic Republic of the Congo) contributed in opposite directions to the global net sink of -3.4 Gt $CO_2 yr^{-1}$ over 2001–2023. The visualization split by the classes Forest, Deforestation, Organic soils, HWP, and Other highlights the large differences in completeness for individual classes, complementing Table 2. For example, we note the incomplete reporting of CO_2 fluxes from organic soils and HWP in developing countries and from Other land uses in the Africa and South-East Asia regions. Furthermore, the maps show that countries with the largest removals from Forest are located in the global North, whereas the Forest class is a net source in some countries in Latin America and Africa regions. The net source or the very low sink from forests in some high-forest cover countries (e.g., Colombia, Peru, Nigeria) contrasts with scientific literature showing that the decline of the tropical forest sinks from primary forests (Brienen *et al.*, 2015; Hubau *et al.*, 2020) is compensated by the increase in carbon sinks from tropical regrowth (Pan *et al.*, 2024; Friedlingstein *et al.*, 2025). The reasons for the relatively low sink in some NGHGI (see Figure 5) include i) lack of data on CO_2 removals in Forest Land (e.g., Peru, Cameroon, Nigeria), and ii) assumptions of carbon equilibrium in primary forests (e.g., Colombia, Ecuador, Papua New Guinea). Differences due to the use of the managed forest proxy, where removals in unmanaged forest areas are not reported because they are considered as not anthropogenic (e.g., Brazil, Chile, Cote d'Ivoire) are minimized by the translation methodology employed in GCB and GFW datasets. A more

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

detailed description of our interpretation of the reported data for each country can be accessed in the info-sheet bar in the LULUCF Data Hub and in the supplementary materials (text_box_iso3_v2.0.csv).

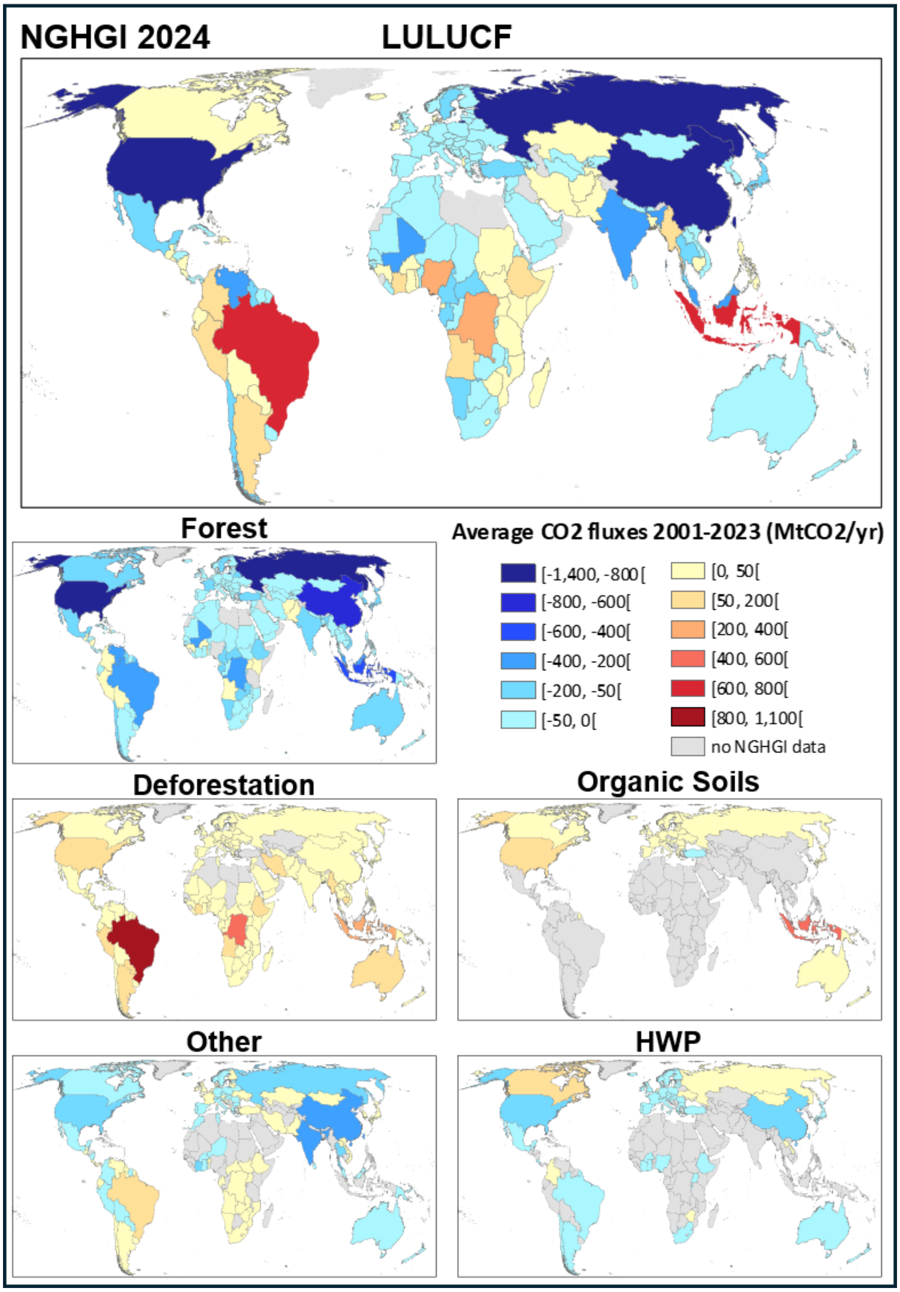

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Figure 5: Spatial distribution by country of the annual average CO_2 fluxes (Mt CO_2yr^{-1}) from LULUCF between 2001 and 2023 from NGHGI submitted by countries to the UNFCCC by April 2025 (version 2.0 of the LULUCF Data Hub). Fluxes are shown aggregated for the whole sector (LULUCF) and split by the classes Forest, Deforestation, Organic soils, HWP, and Other (CO_2 fluxes not included in the previous classes).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

3.2 Global trends of CO_2 fluxes from land-use across datasets (2001-2023)

At the global level, NGHGI data indicate that the LULUCF sector was a net sink of -3.4 Gt CO_2yr^{-1} on average for 2001-2023 (Figure 3; Table 4, and orange line in Figure 6), contrasting with the +4.7 Gt CO_2yr^{-1} net source reported by the GCB 2024 original/reclassified (in dark green in Figure 6; ensemble of four bookkeeping models). The +8.1 Gt CO_2yr^{-1} discrepancy between the GCB and NGHGI estimates is reduced to +1.8 Gt CO_2yr^{-1} when GCB fluxes are translated to use NGHGI definitions of the human-induced CO_2 sink (GCB-translated, light green line in Figure 6; Table 4). In this comparison, a positive gap indicates higher net emissions or lower removals in the global dataset compared to NGHGI, and a negative gap indicates lower net emissions or higher removals.

Estimates for forest-related CO_2 fluxes (sum of CO_2 fluxes from Forest and Deforestation partially including emissions from organic soils; see methods and Table 4a), are +3.9 Gt CO_2yr^{-1} in GCB-original/reclassified and -5.8 Gt CO_2yr^{-1} in GFW-original/reclassified (from step 1 in Figure 1; dark green and dark blue in Figure 6, respectively). After translation (from step 2 in Figure 1; -2.5 Gt CO_2yr^{-1} in GCB-translated and -3.5 Gt CO_2yr^{-1} in GFW-translated; light green and light blue in Figure 6, respectively), both translated datasets closely align with NGHGI (orange; -3.2 Gt CO_2yr^{-1}). The gap for forest-related fluxes between NGHGI and GCB and GFW is thus reduced from +7.1 to +0.7 Gt CO_2yr^{-1} with GCB-translated and from -2.7 Gt CO_2yr^{-1} to -0.3 Gt CO_2yr^{-1} with GFW-translated (Table 4b). Furthermore, with the translation to NGHGI definitions, the large 9.7 Gt CO_2yr^{-1} difference between GCB and GFW is reduced to 1.0 Gt CO_2yr^{-1}.

The largest conceptual discrepancies affecting LULUCF and forest-related CO_2 fluxes arise from the Forest class; NGHGI report a -7.3 Gt CO_2yr^{-1} forest sink, while GCB-original/reclassified estimates -0.7 Gt CO_2yr^{-1} and GFW-original/reclassified estimates -9.1 Gt CO_2yr^{-1}. After translation, estimates are adjusted to -7.0 Gt CO_2yr^{-1} in the GCB and -6.9 Gt CO_2yr^{-1} in the GFW (Table 4a). The translation thus reduces the gap between NGHGI and GCB estimates from +6.6 to +0.3 Gt CO_2yr^{-1} and between NGHGI and GFW from -1.8 to +0.5 Gt CO_2yr^{-1} (Table 4b). These results confirm that the alignment with the NGHGI definition of anthropogenic CO_2 flux in the Forest class (step 2 of the translation methodology; Figure 1) resolves most of the conceptual differences both globally and for major emitting countries (Schwingshackl *et al.*, 2022; Grassi *et al.*, 2023; Friedlingstein *et al.*, 2025).

Global emissions from deforestation over the same period (2001-2023) were, on average, +3.6 Gt CO_2yr^{-1} in NGHGI compared to +4.2 Gt CO_2yr^{-1} in the GCB-original/reclassified and +3.3 Gt CO_2yr^{-1} in the original/reclassified GFW model. Although CO_2 emissions from deforestation are not affected by step 2 of the translation, and thus we do not have "translated" options for this class, decisions about allocation of fluxes to different classes can have substantial effects on our results. The allocation of emissions from shifting agriculture is particularly important – in GCB-original/reclassified the first clearing in shifting cultivation cycles (i.e., clearing of primary forest) is allocated to the class Deforestation whereas subsequent crop and fallow cycles are attributed to Forest. In GFW-original/reclassified fluxes from shifting agriculture are allocated to Deforestation if occurring in primary forests and to Forest if occurring in secondary forests. GCB and GFW have therefore a consistent

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

treatment of CO_2 fluxes from shifting agriculture. For NGHGI, shifting agriculture is very rarely mentioned and explicitly allocated to an IPCC category, and therefore it is unclear in which class these fluxes are allocated. Because land under shifting agriculture cycles often displays the characteristics of temporarily cleared forest, it is likely that these fluxes are reported by countries in the IPCC category 'forest land remaining forest land' and are therefore included in the class Forest in the NGHGI database. However, this is a broad assumption that requires further investigation at country level, where exceptions may occur. If the prevailing land use is crop, then part of the fluxes could be reported in the class deforestation and the subsequent fluxes from crop and fallow cycles in other land use categories. Another minor impact of allocation choices affects CO_2 fluxes from harvest wood products (HWP), which are included under Forest in GCB but reported separately in NGHGI (Figure 6a) and GFW model (although for the GFW model, estimates from HWP are neither included in this study nor in the current versions of the LULUCF Data Hub (versions 1.0 and 2.0). More clarity and enhanced comparability across datasets for both shifting agriculture and HWP are part of the improvement plans for the LULUCF Data Hub.

The translation methodology resolves most of the conceptual differences both globally (Figure 6; Table 4) and regionally (Figure 7). Specifically, the forest-related estimates are relatively similar between the NGHGI and the translated versions of GCB (for 2001-2023) and GFW model (particularly in the last decade). However, we note diverging trends in CO_2 fluxes from Forest, Deforestation, and Other. NGHGI and GCB-translated (in orange and light green, respectively) indicate a stable or slightly increase of forest removals between 2001 and 2023, whereas GFW-original/reclassified and translated (dark and light blue, respectively) show a substantial decline in forest CO_2 removals in the same period. Since GFW uses constant removal factors and static forest area, the forest sink decline can be attributed to increases in estimates of harvest, forest fires and small-scale forest degradation (from shifting agriculture) in the satellite-based observations. This highlights the importance of consistent time-series from satellite-based observations, which require continuity and long-term backward compatibility for space agencies' missions (Poulter *et al.*, 2023). In some regions, namely North America, Europe and West Central-Asia, the decreasing forest sink is also captured by the NGHGI (Figure 7) and is consistent with findings from other studies (Korosuo *et al.*, 2023; Winkler *et al.*, 2023; Ke *et al.*, 2024; Pan *et al.*, 2024). Deforestation trends also differ: both NGHGI and GCB-original/reclassified show decreasing emissions from deforestation over the past two decades, whereas GFW-original/reclassified shows an increase, mainly in tropical countries from Latin America and African regions (Figure 7).

The differing trends at global level between the GFW flux model and aggregated NGHGI was also noted by Gibbs *et al.* (2025), including that the period of divergence is mostly prior to 2010, with convergence thereafter. The authors suggest that the difference is driven by the increasing tree cover loss estimates given by the Global Forest Change product (Hansen *et al.*, 2013) used in the GFW carbon flux model.. The possibility that the Global Forest Change product under-detected tree cover loss in the early years of the timeseries and the risk of temporal inconsistencies in the product are discussed by Gibbs *et al.* (2025) and elsewhere (Galiatsatos *et al.*, 2020; Ceccherini *et al.*, 2021; Palahí *et al.*, 2021; Vancutsem *et al.*, 2021). For example, Vancutsem *et al.* (2021) compared areas of deforestation from the global tropical moist forests (TMF) dataset with the Global Forest Change product and noted that TMF depicts 61.4% more deforested area than Global Forest Change for the

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

2001-2010 decade; yet, for the 2010-2019 decade, deforestation in Global Forest Change is larger, as it maps as forest loss all the deforestation areas in TMF plus 5.7% of the areas mapped in TMF as forest degradation. Temporal inconsistencies can exist in any EO product, because of sensor degradation or sensor and technology changes between successive missions (Roy *et al.*, 2016; Vogeler *et al.*, 2018) or algorithm changes. For EO products to be useful in global modelling and NGHGI, it is important that space agencies ensure long-term backward compatibility of the data provided (Melo *et al.*, 2023).

There is also a difference between GCB-original/reclassified and aggregated NGHGI estimates for the class Other, which includes most CO_2 fluxes from Other IPCC land use categories (i.e., cropland, grassland, wetlands, settlements and other land; both for land remaining in the same land use category and transitions between these categories; Table 1) that are not allocated in the NGHGI database to the classes Deforestation and Organic soils. In NGHGI, Other is an increasing net sink of -0.3 Gt CO_2yr^{-1} whereas the GCB indicates a stable small source of 0.3 Gt CO_2yr^{-1}. In the next section we assess agreement and disagreement at the country level, which can provide some clarity on the differences.

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Preprint. Discussion started: 11 February 2026

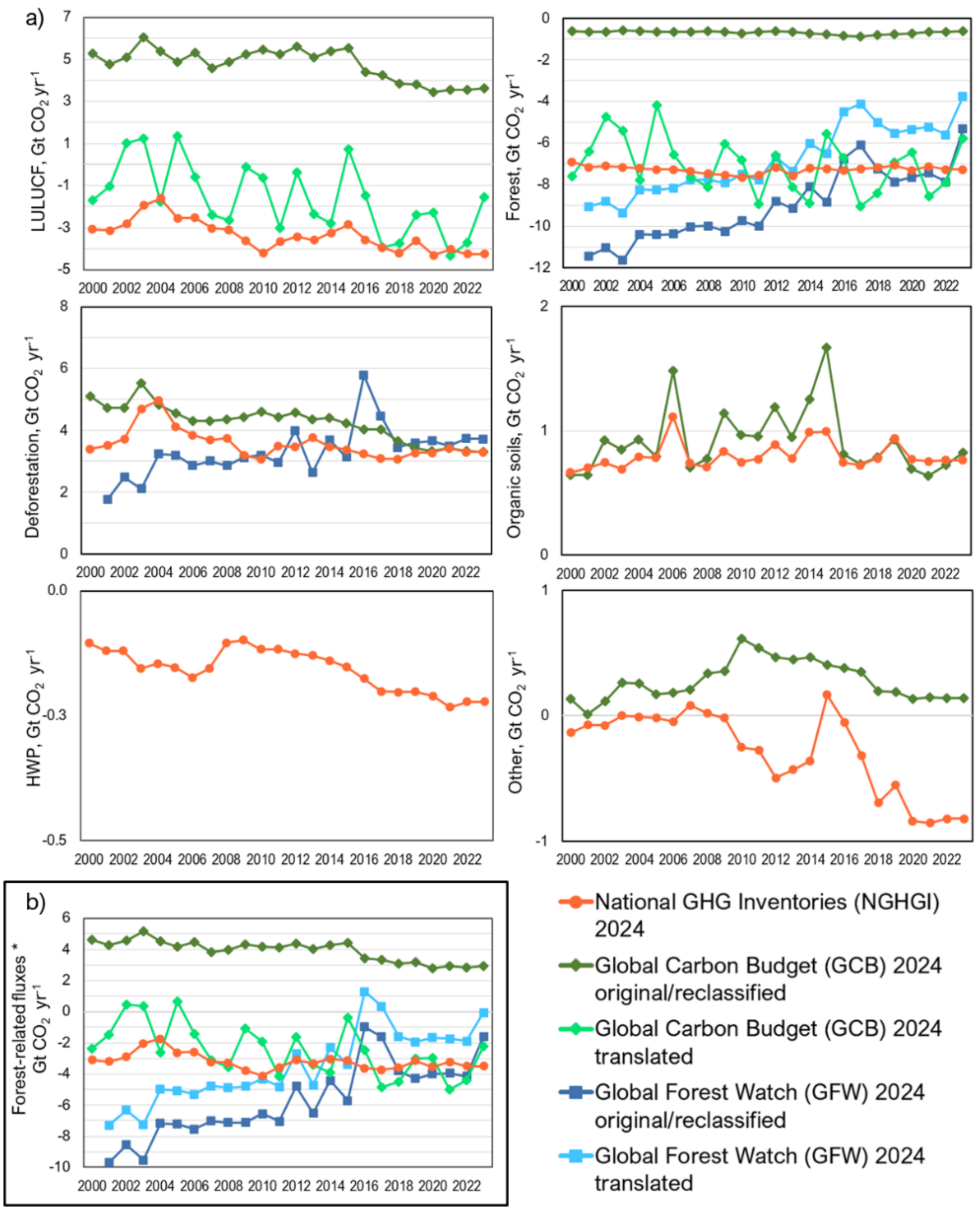

Figure 6: Timeseries of CO_2 fluxes from LULUCF between 2000 and 2023: (a) aggregated for the LULUCF sector and split by the classes Forest, Deforestation, Organic soils (from various land uses), HWP, and Other (CO_2 fluxes not included in the other classes, see text for details on what Other includes in the various datasets). Three different datasets are displayed: i) the NGHGI database compiled by the JRC including NGHGI submitted to the UNFCCC and the Paris Agreement (version 2.0, cut-off date April 2025; in orange), ii) the Global Carbon Budget (GCB) 2024, in two shades of green – in dark green GCB-original/reclassified, and in light green GCB-translated to the NGHGI definition of human-induced CO_2 sink –, and iii) the Global Forest Watch (GFW) in two shades of blue – in dark blue GFW-original/reclassified, and in light blue GFW-translated to the NGHGI definitions. Note that deforestation in GFW includes emissions from organic soils in deforested areas. Panel b) shows the timeseries of forest-related CO_2 fluxes; *for

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

comparability with GFW, forest-related fluxes in NGHGI and GCB (original/reclassified and translated) include CO_2 fluxes from Forest, Deforestation and emissions from Organic Soils in Indonesia which are largely associated to deforestation.

Table 4. Average CO_2 flux estimates for the period 2001-2023 (Gt $CO_2 yr^{-1}$) for each land use class and aggregated for LULUCF and forest-related fluxes: a) as estimated by the different datasets – i.e., NGHGI, GCB 2024 original/reclassified (step 1 in Figure 1) and translated (step 2), and GFW 2024 original/reclassified (step 1) and translated (step 2) –, and b) as the difference between datasets. Minus (-) and plus (+) signs denote removals and emissions from/to the atmosphere, respectively. When comparing datasets (b), a minus (-) sign denotes higher net removals (or lower net emissions) and a plus (+) sign denotes higher net emissions (or lower net removals). * for comparability with GFW totals for forest-related fluxes (Forest and Deforestation including emissions from organic soils), NGHGI and GCB (original/reclassified and translated) include CO_2 fluxes from Forest, Deforestation and emissions from Organic Soils in Indonesia which are largely associated to deforestation.

a) CO_2 flux estimates per dataset (average 2001-2023; Gt $CO_2 yr^{-1}$)						b) difference between datasets (average 2001-2023; Gt $CO_2 yr^{-1}$)					
Classes of land-use	NGHGI	GCB 2024		GFW 2024		GCB 2024		GFW 2024		GCB - GFW	
		original / reclassified	translated	original / reclassified	translated	reclassified - NGHGI	translated - NGHGI	reclassified - NGHGI	translated - NGHGI	reclassified	translated
LULUCF	-3.4	4.7	-1.6			8.1	1.8				
Forest-related *	-3.2	3.9	-2.5	-5.8	-3.5	7.1	0.7	-2.7	-0.3	9.7	1.0
Forest	-7.3	-0.7	-7.0	-9.1	-6.8	6.6	0.3	-1.8	0.5	8.5	-0.2
Deforestation	3.6	4.2		3.3		0.6		-0.3		0.9	
Other	-0.3	0.3				0.6					
Organic soils	0.8	0.9				0.0					
HWP	-0.2										

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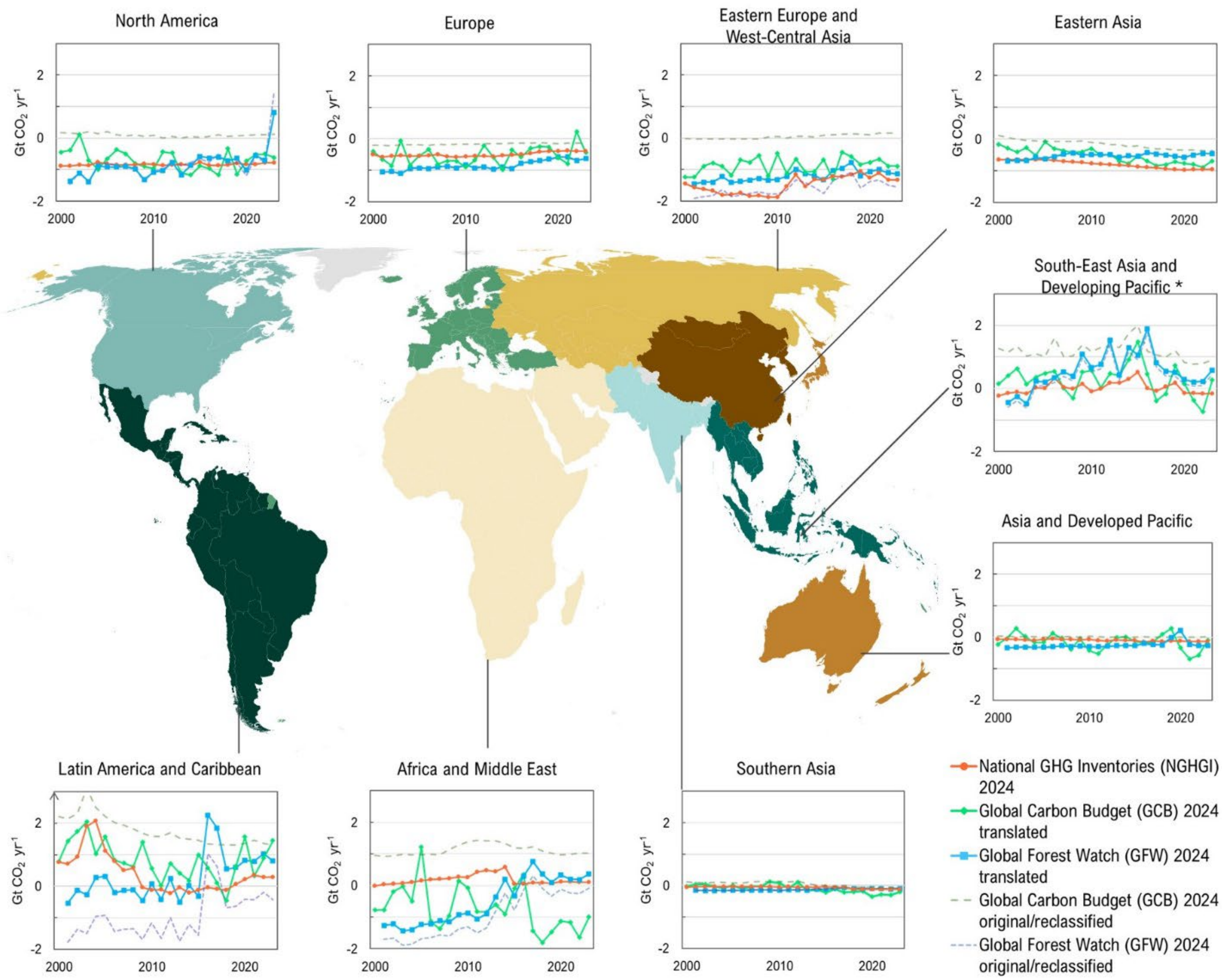
Preprint. Discussion started: 11 February 2026



665 **Figure 7:Regional breakdown of "forest-related" annual CO_2 fluxes between 2001 and 2023 (i.e., sum of the classes Forest and Deforestation) as estimated by three different datasets: National GHG Inventories database (NGHGI 2024, in orange), Global Carbon Budget 2024 in the original/reclassified version (step 1) and translated (step 2) to the NGHGI definition of human-induced CO_2 sink (GCB-original/reclassified and GCB-translated, in dashed and light green respectively) and Global Forest Watch 2024 original/reclassified and translated to the NGHGI definitions (GFW-original/reclassified and GFW-translated, in dashed and light**
670 **blue respectively). Each panel shows the sum of the annual fluxes reported by the countries in each region. Regional groupings follow the classification adopted in the IPCC AR6 WGIII, (IPCC 2022). * For the South-East Asia and Developing Pacific region, exceptionally, emissions from organic soils in Indonesia are also included in NGHGI and GCB estimates for a more consistent comparison with GFW.**

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

3.3 Country-level differences in CO_2 fluxes between independent datasets and national GHG Inventories

In the previous sections we showed that the translation methodology resolves conceptual differences globally by reducing the gap in forest-related estimates (classes Forest, Deforestation, and partially Organic Soils) from +7.1 to +0.7 Gt CO_2yr^{-1} between GCB-translated and NGHGI and from -2.7 to -0.3 Gt CO_2yr^{-1} between GFW-translated and NGHGI (Table 4). However, the level of agreement varies across countries (Figure 8). For forest-related CO_2 fluxes, most of the global discrepancy between GCB-translated and NGHGI and between GFW-translated and NGHGI is predominant in 19 countries (Figure 8a and Table 5a). Both GCB-translated and GFW-translated tend to differ from NGHGI in the same set of countries (n=14). For Other land uses, large differences between GCB-original/reclassified and NGHGI are found in four countries (Figure 8b and Table 5b; differences above ±0.1 Gt CO_2yr^{-1}). Only countries with estimates in both datasets are included in this comparison: i) 185 countries plus EU27 in the comparison GCB-translated vs. NGHGI and GFW-translated vs. NGHGI for forest-related CO_2 fluxes; and ii) 105 in the comparison GCB-original/reclassified vs. NGHGI for the class Other land uses.

For the comparison of GCB vs. NGHGI, Schwingshackl *et al.* (2022) showed for eight major emitting countries that the translation in general greatly reduces the mismatch, and that country-specific reasons on both the GCB and NGHGI side can explain the remaining discrepancies. Here we analyse the remaining discrepancies in all countries, identifying those countries where GCB-translated either shows higher net removals than NGHGI (n=74; corresponding to an aggregated -2.5 Gt CO_2yr^{-1} higher net sink in GCB-translated than in NGHGI) or higher net emissions than NGHGI (n=111; corresponding to an aggregated higher source of +3.3 Gt CO_2yr^{-1} in GCB-translated than NGHGI) (Table 4). At the global level, these two sets of countries compensate each other to achieve the +0.7 Gt CO_2yr^{-1} (2001-2023) difference between GCB-translated and NGHGI (Table 4b), an apparent balance that masks substantial differences at the country level.

The key countries contributing to a larger net sink in GCB-translated compared to NGHGI are: Nigeria, Democratic Republic of the Congo (DRC), Angola, Cote d'Ivoire, Canada, and Colombia (Figure 8a and Table 5a). These six countries have individually higher net removals or lower net emissions larger than 0.1 Gt CO_2yr^{-1} (average 2001-2023) in the GCB-translated estimates than the NGHGI, corresponding to a total difference of -1.1 Gt CO_2yr^{-1} (43% of the -2.5 Gt CO_2yr^{-1} higher net sink in GCB-translated at the global level). The key countries contributing to a larger net source in GCB-translated compared to NGHGI are: Russia, Venezuela, USA, Malaysia, Mali, Brazil, China, Indonesia, Guyana, Mexico, and Namibia. These 11 countries have individually higher net emissions or lower net removals larger than 0.1 Gt CO_2yr^{-1} in GCB-translated than NGHGI (the largest discrepancy is found in Russia, with a difference larger than 0.3 Gt CO_2yr^{-1}; Figure 8a.i), corresponding to a total difference of +2.3 Gt CO_2yr^{-1} (73% of the total +3.3 Gt CO_2yr^{-1} higher net source in GCB-translated at the global level; Table 5a).

For GFW, while the translation achieves excellent global agreement with NGHGI (a difference of only -0.3 Gt CO_2 yr^{-1} for forest-related fluxes between 2001-2023 on average; Table 4), large differences can occur at the country level. GFW-translated estimates a larger net sink compared to NGHGI in 96 countries, corresponding to a difference of -3.0 Gt CO_2yr^{-1}. These higher net removals (or lower net emissions) are partially compensated by estimates of higher net emissions (or lower net removals) in the remaining 89 countries, collectively corresponding to +2.7 Gt CO_2yr^{-1} in GFW compared to NGHGI. Heinrich *et al.* (2023) has shown for three major emitting countries that the translation in general reduces the mismatch, and that country-specific reasons on both GFW and NGHGI side explain some of the remaining discrepancies.

Key countries contributing to the larger net sink (with a difference from NGHGI larger than 0.1 Gt CO_2yr^{-1}) are Nigeria, DRC, Brazil, Angola, Cote d'Ivoire, Argentina, Canada, and Australia (Table 5a). These eight countries collectively account for a difference of -1.5 Gt CO_2yr^{-1} (corresponding to 51% of the -3.0 Gt CO_2yr^{-1} at the global level; Table 5a) in GFW-translated compared to NGHGI. In addition, when aggregating the forest-related sink across the EU member states (EU 27), GFW-translated estimates a substantially larger net sink (>0.3 Gt CO_2yr^{-1}) than the EU27 NGHGI. For Nigeria, GFW-translated also estimates removals that are more than 0.3 Gt CO_2yr^{-1} greater than in NGHGI, paired with a disagreement in the sign of the fluxes, with Nigeria's NGHGI reporting a net source and GFW-translated a net sink (black colour in Figure 8a.ii; Table 5a). Key countries contributing to the larger net source (with a difference to NGHGI above 0.1 Gt CO_2yr^{-1}) are Malaysia, Russia, Venezuela, China, Mali, Guyana, USA, and Namibia. The higher net emissions in GFW-translated for these eight countries correspond to a total difference of +2.3 Gt CO_2yr^{-1} (66% of the total +2.7 Gt CO_2yr^{-1} higher net source in GFW-translated at the global level). The differences between GFW-translated and NGHGI are larger than 0.3 Gt CO_2yr^{-1} in two countries: Malaysia and Russia. In Russia, GFW-translated shows lower net removals than NGHGI. In Malaysia, GFW-translated reports higher net emissions and disagrees in sign with NGHGI, with GFW-translated estimating a net source while the NGHGI reports a net sink (black colour in Figure 8a.ii; Table 5a).

For Other land uses, the GCB-original/reclassified estimates higher net removals than NGHGI in 60 countries, corresponding to an aggregated larger sink of -0.6 Gt CO_2yr^{-1} on average in 2001-2023 (Table 5b). For the remaining 58 countries with data on Other land uses, GCB-original/reclassified estimates higher net emissions of +1.2 Gt CO_2yr^{-1}. Therefore, the higher net emissions or lower net removals in GCB-original/reclassified compared to NGHGI are partially compensated by the higher net removals of lower net emissions, yielding a net difference of +0.6 Gt CO_2yr^{-1} in Other land uses between the GCB-original/reclassified and NGHGI in the period 2001-2023 (Table 4b). Key contributing countries with differences above 0.1 Gt CO_2yr^{-1} are China, India and Nigeria, with lower net removals in GCB-original/reclassified than in the NGHGI, and Indonesia with lower net emissions above 0.3 Gt CO_2yr^{-1} (Figure 8b, Table 5b).

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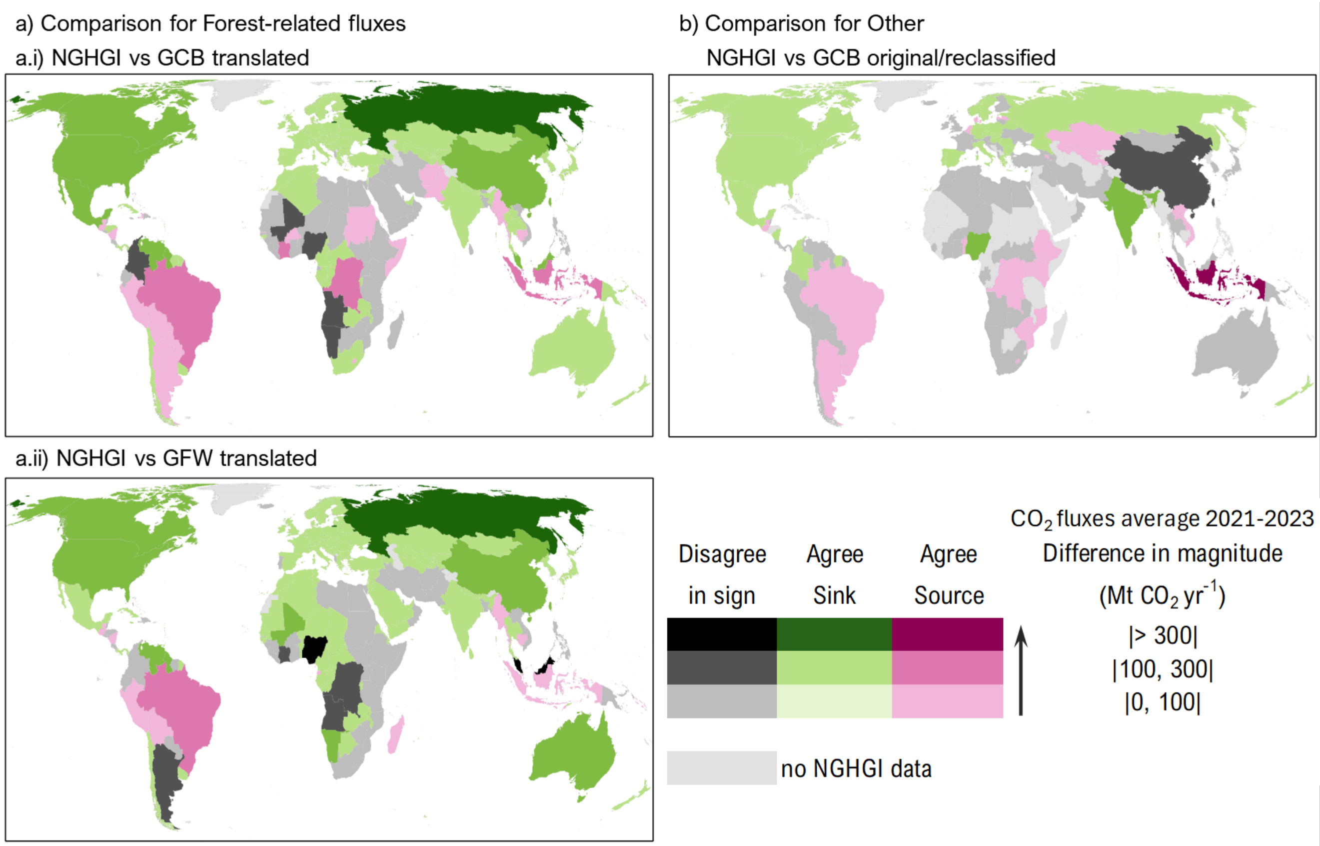

Figure 8: Comparison of the average annual CO_2 fluxes at country level between NGHGI and independent estimates. In panel a) the forest-related CO_2 fluxes from NGHGI, including the classes Forest, Deforestation and partially Organic Soils, are compared to a.i) estimates from the Global Carbon Budget (GCB) 2024 translated to NGHGI definitions and to a.ii) estimates from the Global Forest Watch (GFW) 2024 translated to NGHGI definitions. For a more like-for-like comparison with GFW including emissions from organic soils in the class deforestation (see Table 1), emissions from organic soils in Indonesia are included in the NGHGI and GCB estimates. In panel b) the CO_2 fluxes from the class Other are compared between NGHGI and GCB 2024 original/reclassified. The comparison between pairs of products highlights in darker colours the countries where the disagreement is of higher magnitude and in lighter colours the countries where the magnitude of the difference is lower (> 300, 300-100, and 100-0 Mt CO_2yr^{-1} difference in absolute values on average in 2001-2023). The greyscale shows countries where datasets disagree whether the country is a source or a sink (i.e., sign disagreement), magenta indicates that datasets agree the country is a source, and green indicates that datasets agree the country is a sink. Only countries with estimates in both products being compared are illustrated in the map.

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Preprint. Discussion started: 11 February 2026

Table 5: Average annual CO_2 fluxes from countries with large disagreement (classes >300 and 100-300 Mt $CO_2 yr^{-1}$ difference in absolute values as illustrated in Figure 8; average 2001-2023) between NGHGI and estimates from the Global Carbon Budget (GCB) 2024 and the Global Forest Watch (GFW) 2024 for a) Forest-related emissions (as the sum of the classes Forest, Deforestation and partially Organic soils; see Methods and *) and b) the class Other (comparison only with GCB-original/reclassified) to match the panels in Figure 8. * Because GFW includes emissions from organic soils in deforested pixels, here NGHGI and GCB also include emissions from organic soils in Indonesia. † Only countries with estimates in both products being compared are included in the totals: a) n=185 countries plus EU27, and b) n=105 countries.

Classes of disagreement		a) Forest-related fluxes								b) Other			
		NGHGI vs GCB translated				NGHGI vs GFW translated				NGHGI vs GCB original/reclassified			
sign	difference in magnitude ($MtCO_2 yr^{-1}$)	Country	NGHGI ($MtCO_2 yr^{-1}$)	GCB	difference	Country	NGHGI ($MtCO_2 yr^{-1}$)	GFW	difference	Country	NGHGI ($MtCO_2 yr^{-1}$)	GCB	difference
Disagree in sign	|>300|					Malaysia	-238	154	392				
						Nigeria	284	-47	-330				
	|100, 300|	Nigeria	284	-5	-289	DRC	231	-15	-246	China	-231	6	237
		Mali	-211	3	214	Angola	57	-108	-164				
		Angola	57	-142	-199	Cote d'Ivoir	136	-24	-160				
		Colombia	85	-33	-118	Argentina	71	-77	-148				
		Namibia	-105	4	109								
Agree it is a sink	|>300|	Russia	-1,353	-768	585	Russia	-1,353	-1,049	305				
						EU27	-380	-680	-300				
	|100, 300|	Venezuela	-302	-10	292	Venezuela	-302	-46	257	India	-238	-5	233
		Malaysia	-238	-16	222	China	-710	-487	223	Nigeria	-120	-1	119
		USA	-747	-476	274	Mali	-211	-1	210				
		China	-710	-502	208	Guyana	-144	-2	142				
		Canada	-86	-231	-145	Canada	-86	-213	-127				
		Guyana	-144	-14	130	USA	-747	-626	122				
		Mexico	-177	-60	117	Australia	-1	-115	-114				
						Namibia	-105	0	105				
Agree it is a source	|>300|									Indonesia	433	41	-393
	|100, 300|	DRC	231	14	-217	Brazil	749	547	-202				
		Brazil	749	960	211								
		Cote d'Ivoir	136	21	-115								
		Indonesia*	237	368	131								
Main countries		GCB higher sink			-1,084	GFW higher sink			-1,493	GCB higher sink			-393
		GCB higher source			2,361	GFW higher source			1,755	GCB higher source			590
All countries †		GCB higher sink			-2,530	GFW higher sink			-2,956	GCB higher sink			-648
		GCB higher source			3,262	GFW higher source			2,673	GCB higher source			1,218

3.4 Insights from the countries where large discrepancies in forest-related fluxes remain after translation

A closer inspection of the NGHGI of the highlighted countries in Figure 8 and Table 5 gives additional insight and can partially explain the existing differences (Figure 9 to Figure 12) and compensatory effects when comparing in GCB/GFW-translated to NGHGI. This section explores these differences, discussing when possible the potential reasons. In principle, these discrepancies can be attributed to three categories: (i) Inaccurate NGHGI estimates, e.g. due to incomplete reporting of land use categories or carbon pools, or to inaccurate input data on activity data (area) or emission/removal factors. In particular, here we follow the criteria suggested by Grassi *et al.* (2022) to consider a forest sink as "implausible", i.e. when the implied net emission factor (net sink per unit of area) for forest land is greater than -10 tCO_2 ha^{-1} yr^{-1} at country level, if occurring over >1 Mha; the rationale of > 1 Mha aims to exclude the impact of fast-growing plantations, which rarely exceed this threshold. While these criteria are obviously an approximation, we consider them useful to highlight likely problems in the NGHGI. (ii) Inaccurate models' estimates, e.g. due to inaccurate input data (e.g., tree cover or land use change, growth factors, etc.) or assumptions in GCB's bookkeeping models or GFW, or in the DGVMs used to translate the GCB data. (iii) Inaccurate translation, for example a temporal mismatch in a few cases where country-based information on managed forest area used to filter the DGVM data (in the translation of GCB) or to remove fluxes from unmanaged forests (in the translation of GFW) is not entirely aligned with the latest version of the NGHGI database. This is because, at the time of the translation of GCB 2024 (Friedlingstein *et al.*, 2025) and GFW 2024 (Gibbs *et al.*, 2025), the information on managed area used was from version 1.0. This discrepancy, whose impact is small at global level, will be addressed in future translations of datasets and future versions of the Data Hub.

Both GCB-translated and GFW-translated show a larger net sink than NGHGI (above 0.1 Gt CO_2yr^{-1} difference; Table 5) in five countries: Nigeria, DRC, Cote d'Ivoire, Canada and Angola. The GCB-translated also estimates a larger net sink in Colombia, and the GFW-translated in Argentina, Brazil, Australia, and EU27. Both GCB-translated and GFW-translated show a larger net source than the NGHGI (difference above 0.1 Gt CO_2yr^{-1}; Table 5) in eight countries: Russia, Venezuela, USA, Malaysia, Mali, China, Guyana, and Namibia. The GCB-translated also estimates a larger net source than the NGHGI (above 0.1 Gt CO_2yr^{-1}) in Brazil, Mexico, and Indonesia. In eight countries, the translation methodology worsens the gap: Nigeria, Cote d'Ivoire, and Angola for both GCB/GFW-translated, Colombia only for GCB-translated, and Guyana, Venezuela, Mexico, and DRC only for GFW-translated.

After translation, the regions (same as used in IPCC, 2022) where we still find most of the variability between datasets in forest-related fluxes (Figure 7) are Africa and Middle East (Figure 9), Latin America and Caribbean (Figure 10), and South-East Asia and Developing Pacific (Figure 11) with other countries in the rest of the World (Figure 12) also contributing to the remaining gap. The 19 countries plus the EU27 with the most substantial discrepancies in forest-related fluxes (differences to NGHGI above ±0.1 Gt CO_2yr^{-1}; Figure 8 and Table 5) are grouped by regions to explore reasons for the existing differences: i) Cote d'Ivoire, DRC, Mali, Namibia, and Nigeria in Africa and Middle East (Figure 9; n = 5); ii) Argentina, Brazil, Colombia, Guyana, Mexico and Venezuela in Latin America and Caribbean (Figure 10; n = 6); iii) Malaysia and Indonesia in South-East Asia and Developing Pacific (Figure 11; n = 2); and iv) Australia, Canada, China, EU27, Russia, and USA as key contributing countries from the other regions of the World (Figure 12, n = 6). The country-level discussions below are meant to be a starting point for exploring country-level differences between datasets, not an explanation.

3.4.1 Africa and Middle East region

The Africa and Middle East region is where we find the largest differences between NGHGI and both GCB-translated and GFW-translated (Figure 7; Figure 9). For the Forest class, the NGHGI estimate in the Africa and Middle East region is -1.3 Gt CO_2yr^{-1}; the GCB-original/reclassified estimate is +0.8 Gt CO_2yr^{-1} and the GCB-translated estimate is -1.7 Gt CO_2yr^{-1}. For the GFW dataset, the original/reclassified estimate for the Forest class (-1.3 Gt CO_2yr^{-1}) is closer to the NGHGI estimates than the translated version (-0.8 Gt CO_2yr^{-1}; Figure 9; also, although not so markedly, in the South East Asia region).

Larger net sink compared to NGHGI

Both translated GCB/GFW indicate a higher forest-related CO_2 sink than NGHGI in the same set of countries (n=4; Figure 8 and Table 5). Both Nigeria and Cote d'Ivoire have submitted the first BTR in 2024, while we rely on less complete data from the National Inventory Report (2023) for the DRC and the Second National Communication (2021) for Angola.

Nigeria submitted a complete timeseries 2000-2022 for LULUCF fluxes in the common reporting tables (CRTs). However, all LULUCF fluxes in the CRTs are allocated to the category 'forest land remaining forest land', including those due to deforestation and wood harvest. In the NGHGI database we thus use information from Nigeria's REDD+ submission (2019) to allocate part of the emissions reported in the Forest Land category to our class deforestation: an estimate (0.03 Gt CO_2yr^{-1}) consistent with GCB-original/reclassified (0.03 Gt CO_2yr^{-1}) and GFW-original/reclassified (0.01 Gt CO_2yr^{-1})(Figure 9). The remaining net emissions included in the category Forest Land in Nigeria's NGHGI (+0.25 Gt CO_2yr^{-1} on average) were left in the Forest class of the NGHGI database and contrast with the increasing net removal estimates of GCB-translated (-0.04 Gt CO_2yr^{-1}) and decreasing net removals in GFW-translated (-0.05 Gt CO_2yr^{-1}). This leads to a difference in magnitude in forest-related fluxes >0.1 Gt CO_2yr^{-1} (on average) and a disagreement in the sign (NGHGI reports a net source and the translated GCB/GFW yields net sinks; Figure 8 and Table 5). It also contributes to the contrasting trend observed in the Africa region between the stable to decreasing forest sink in NGHGI and the increasing forest sink in GCB-translated (Figure 9). Although Nigeria mentions in their national inventory document that removals from forest growth are included, the document and CRT do not indicate the magnitude and extent to which these removals are included. In the BUR, Nigeria states that all land is managed, although there is no information on area extent in the CRTs. In the decision tree with information on the use of managed land proxy (Figure 2), Nigeria is included in the group of countries where managed forest proxy is not explicitly applied (A4) and where it is unclear whether removals from forest land are fully included (B2). A more in-depth and accurate comparison and translation requires more clarity from and collaboration with Nigeria's NGHGI compilers.

Cote d'Ivoire also submitted a complete time series 2000-2022 in CRTs but only aggregated to total LULUCF. Thus, the NGHGI database uses information from the National Inventory Report to disaggregate LULUCF totals (see description in supplementary text_box_iso3.csv). Most removals in the Forest class in the NGHGI are from 'forest land remaining forest land' and the magnitude of the estimate is relatively similar to the other datasets (NGHGI = -0.03 Gt CO_2yr^{-1}; GCB-translated = -0.05 Gt CO_2yr^{-1}; GFW-translated = -0.03 Gt CO_2yr^{-1}). In the case of Cote d'Ivoire, the large mismatch (above 0.1 Gt CO_2yr^-

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

[1] on average) is due to differences in deforestation, with NGHGI estimating higher net emissions (+0.16 Gt CO_2yr^{-1}) than GCB-original/reclassified (+0.07 Gt CO_2yr^{-1}) and GFW-original/reclassified (+0.01 Gt CO_2yr^{-1}).

In DRC, the higher forest-related net sink in GCB-translated and GFW-translated compared to NGHGI is also mostly due to higher emissions from deforestation in the NGHGI (+0.56 Gt CO_2yr^{-1}) compared to GCB-original/reclassified (+0.40 Gt CO_2yr^{-1}) and GFW-original/reclassified (+0.21 Gt CO_2yr^{-1}). The large forest sink reported by DRC (-0.33 Gt CO_2yr^{-1}) is in between the estimates of GCB-translated (-0.38 Gt CO_2yr^{-1}) and GFW-translated (-0.23 Gt CO_2yr^{-1}). For the DRC, the translation methodology reduced the gap with NGHGI in the forest class for both datasets. The NGHGI database uses data from the NIR (2023) with a complete annual timeseries 2000-2018. According to the NIR and BUR, the increase in forest removals between 2000 and 2018 is due to the restoration of native forests and forest growth, and emissions from deforestation may partially include emissions from forest degradation due to methodological limitations and an operational definition of forest land.

For Angola, the NGHGI database uses data from the 2021 national communication with annual data for the period 2005-2018. Similarly to Nigeria, also in Angola the estimates for deforestation are relatively similar between datasets and the main differences stem from the Forest class. On average for 2001-2023, the forest class is a small net source in the NGHGI (close to zero) and a sink (>0.1 Gt CO_2yr^{-1}) in both GCB-translated and GFW-translated. In the case of Angola, the GCB-original/reclassified estimates for the forest class (also close to zero) are closer to the NGHGI estimates than GCB-translated (-0.2 Gt CO_2yr^{-1}). In the national communication it is not clear if forest fluxes include removals from 'land converted to forest land' (afforestation) and the extent to which forest growth is included remains uncertain (group B2 of the decision tree in Figure 2).

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

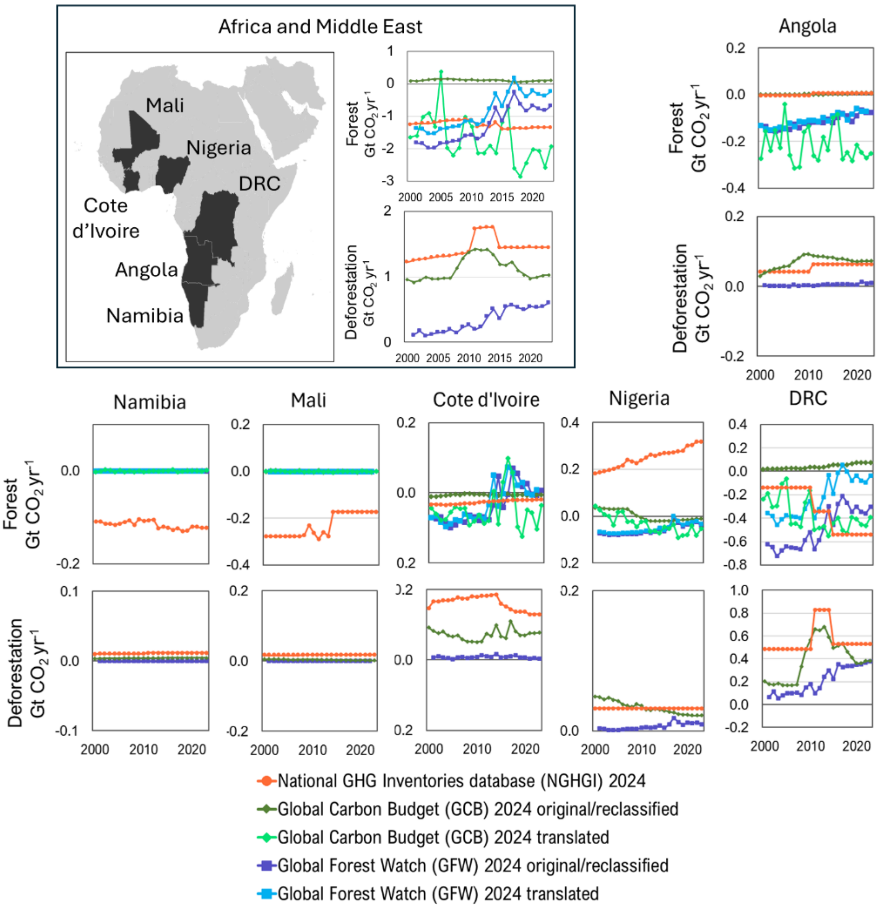

Figure 9. Timeseries for the Africa and Middle East region of annual CO_2 fluxes (2000-2023) for the classes Forest and Deforestation as estimated by: National GHG Inventories database (NGHGI, in orange), Global Carbon Budget 2024 original/reclassified (step 1 in Figure 1) and translated to the NGHGI definition of human-induced CO_2 sink (step 2 in Figure 1; GCB-original/reclassified and GCB-translated in dark and light green, respectively) and Global Forest Watch 2024 in the original version and translated to the NGHGI definitions (GFW-original/reclassified and GFW-translated in dark and light blue, respectively). Timeseries are shown for the whole region and for countries with the largest differences between datasets (see Figure 8 and Table 5) – Angola, Cote d'Ivoire, Democratic Republic of the Congo (DRC), Mali, Namibia and Nigeria.

Larger net source compared to NGHGI

Both GCB/GFW-translated indicate a higher forest-related CO_2 source than NGHGI (above 0.1 Gt CO_2yr^{-1} on average) in Mali and Namibia. Namibia submitted a BTR in 2024 and the information in the NGHGI database is extracted from CRTs with annual estimates for 2000-2022. For Mali, the NGHGI database relies on data from the latest BUR submitted in 2023 under pre-Paris reporting rules which includes annual estimates for 2013-2019.

Mali reports a very large forest sink in its NGHGI (-0.23 Gt CO_2yr^{-1}; Figure 9). In our assessment, this sink would be "implausible" if considering the forest area of 13 Mha reported to FAO FRA 2020. In the 2023 BUR, Mali reports a very large area of forest land of 63 Mha for a total territory of 124 Mha. Even though the net removal per unit area (implied net emission

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

factor) is not implausible (-3.7 $tCO_2\ ha^{-1}\ yr^{-1}$), we still consider the total forest sink implausible due to the extremely large area being reported as forest land ("Tropical Mixed Hardwoods") – in contrast to FAO FRA 2020 (13 Mha) and any satellite data – combined with a relatively high annual tree growth factor or emission/removal factor (6.8 t dry matter yr^{-1}). By contrast, GCB-translated shows a small source for the Forest class (+0.003 Gt $CO_2 yr^{-1}$) and GFW-translated as a small forest sink (-0.001 Gt $CO_2 yr^{-1}$), both resulting in much higher net emissions compared to NGHGI.

Namibia is in a similar situation to Mali. Emissions from deforestation are negligible in all datasets while for Forest, the NGHGI reports a large forest sink (-0.12 Gt $CO_2 yr^{-1}$) compared to a negligible net source in GCB-translated and a negligible net sink in GFW-translated. Consistently with Grassi *et al.* (2022), we consider the Forest sink reported by Namibia implausible. In the 2024 BTR, Namibia reports a very large area of managed forest (66 Mha for a total territory of 82 Mha) and includes removals from bush encroachment and its thickening when these areas meet the biophysical thresholds of the national forest definition. Although the annual growth factors used by Namibia are lower than the IPCC defaults for African drylands (0.4 tdm/yr in forest and 0.8 tdm/yr in woodland, including bush encroachment), the large area of managed forest likely explains the (implausibly) high removals in the Forest class.

3.4.2 Latin America and Caribbean region

Larger net sink compared to NGHGI

In the Latin America region, the translated GCB shows higher net removals than NGHGI in Colombia and the translated GFW shows higher net removals in Argentina and Brazil (with differences >0.1 Gt $CO_2 yr^{-1}$ on average). These three countries have submitted a BTR in 2024 and the NGHGI database includes complete timeseries with annual data for 2000-2022 (or 2000-2021 for Colombia) available from CRTs.

In Colombia (Figure 10), NGHGI reports a net forest source in the forest class (+0.05 Gt $CO_2 yr^{-1}$) contrasting with a forest sink in the translated GCB (-0.12 Gt $CO_2 yr^{-1}$). The translated GFW also estimates a sink, causing a difference in sign (Figure 8), but the magnitude is lower (-0.07 Gt $CO_2 yr^{-1}$) and the higher removals are mostly compensated by emissions from deforestation. In the BTR 2024, Colombia considers all forest land managed (60 Mha). Forest fluxes in NGHGI include emissions from the establishment of plantations and removals from the annual increment in plantations, as well as fluxes from transitions between forest classes (stock change) in natural forests. However, the NGHGI does not consider removals from annual tree growth in natural forests due to lack of information on annual tree growth and biomass increment (group A1B3 in the decision tree of Figure 2). In this case, natural forest removals in the NGHGI may be under-estimated and the translation methodology of adding the natural sink in managed forests from DGVMs to bookkeeping models in GCB increases the gap to NGHGI. Expert judgement was applied in the case of Colombia: in the alignment (step 2 of the translation), Colombia was assigned to group A4 in the decision tree (Figure 2) and natural forests may have been partially considered managed (i.e., if not primary/intact forests).

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Preprint. Discussion started: 11 February 2026

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In Argentina, estimates for deforestation are consistent among datasets and differences are due to fluxes in the Forest class. Argentina's NGHGI reports a small forest sink of close to zero, while GFW-translated estimates a larger net forest sink of -0.1 Gt CO_2yr^{-1} (on average for 2001-2023). In the 2024 BUR and CRTs used in version 2.0 of the NGHGI database and LULUCF Data Hub, Argentina reports only 1Mha of forests as managed but 47Mha as unmanaged (group A3 from decision tree in Figure 2). However, at the time GCB-translated (Friedlingstein *et al.*, 2025) and GFW-translated (Gibbs *et al.*, 2025) were estimated, the information we had from Argentina was from pre-Paris reporting (version 1.0 of the NGHGI database) where Argentina was allocated to group A4 of the decision tree in Figure 2 ("managed forest not mentioned / not explicitly applied"). Consequently, the alignment in step 2 of the translation methodology (Figure 1) was not the most appropriate for Argentina. With the updated information on the area of managed land (i.e., update to decision tree 2.0, and consequent update on the managed forest maps used in the translation), we expect a smaller disagreement across datasets in the next version of the LULUCF Data Hub.

In Brazil, GFW-translated shows a greater forest sink (-0.66 Gt CO_2yr^{-1}) than NGHGI (-0.31 Gt CO_2yr^{-1}). Brazil considers almost half of its forest area as managed (235 Mha) which includes protected areas and indigenous lands in the Amazonia biome (group A2 of the decision tree of Figure 2 – "not all forest is managed, country map available"). Although the alignment with the NGHGI definition of anthropogenic CO_2 flux in the Forest class (step 2 of the translation methodology; Figure 1) for Brazil reduces the forest sink from -1.3 Gt CO_2yr^{-1} in GFW-original/reclassified to -0.66 Gt CO_2yr^{-1} in GFW-translated, thus reducing the gap to the NGHGI estimate, the remaining difference in forest-related fluxes is still above 0.1 Gt CO_2yr^{-1} (Figure 8 and Table 5). Possible reasons for this remaining large difference include the higher removal factors applied in GFW compared to national reporting in all forest types (Heinrich *et al.*, 2023).

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Preprint. Discussion started: 11 February 2026

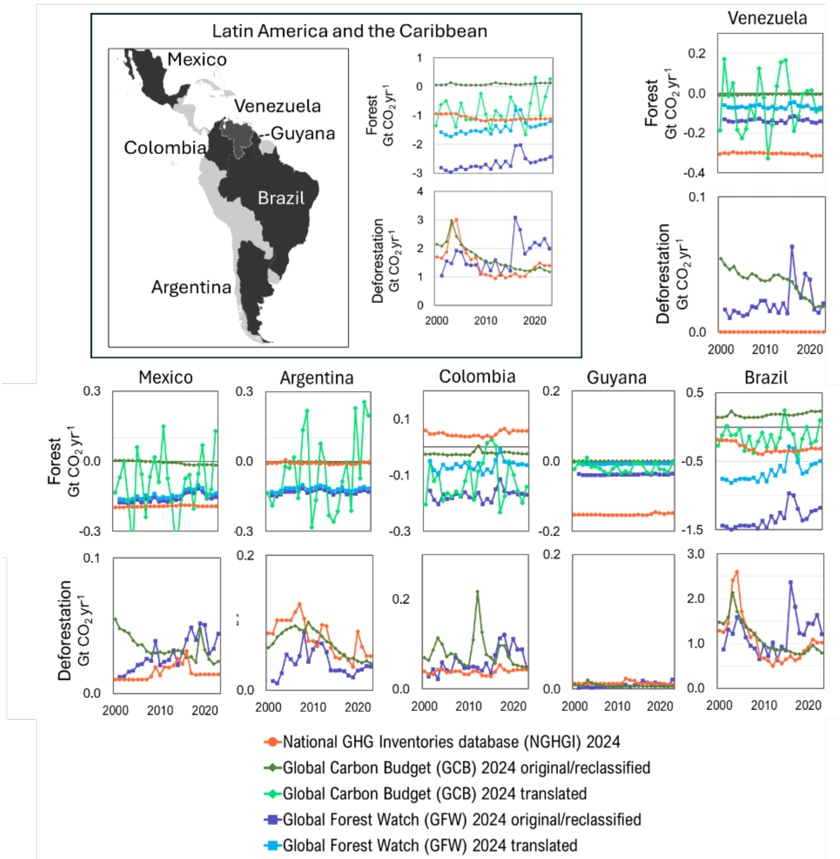

Figure 10. Timeseries for the Latin America and the Caribbean region of annual CO_2 fluxes (2000-2023) for the classes Forest and Deforestation as estimated by: National GHG Inventories database (NGHGI, in orange), Global Carbon Budget 2024 original/reclassified (step 1 in Figure 1) and translated to the NGHGI definition of human-induced CO_2 sink (step 2 in Figure 1; GCB-original/reclassified and GCB-translated in dark and light green, respectively) and Global Forest Watch 2024 in the original version and translated to the NGHGI definitions (GFW-original/reclassified and GFW-translated in dark and light blue, respectively). Timeseries are shown for the whole region and for countries with the largest differences between datasets – Argentina, Brazil, Colombia, Guyana, Mexico, and Venezuela.

Larger net source compared to NGHGI

In the Latin America region, both GCB-translated and GFW-translated estimates lower net removals in Venezuela and Guyana (with differences above ±0.1 Gt $CO_2 yr^{-1}$; Table 5), which result in higher net emissions in GCB-translated and GFW-translated compared to NGHGI at the global level. GCB-translated estimates higher net emissions (or lower removals) also in Brazil and Mexico. Venezuela, Guyana and Brazil have submitted a BTR in 2024 and the NGHGI database includes complete timeseries with annual data for 2000-2022 available from CRTs. For Mexico, the NGHGI database (version 2.0) uses information from pre-Paris reporting in the third BUR and corresponding NIR (from 2022) with annual data for LULUCF for 2000-2019. Mexico has submitted the first BTR and CRT in June 2025 (after the cut-off date of version 2.0) and the data will be updated in version 2.1.

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

In Venezuela, the NGHGI reports a large forest sink (-0.30 Gt CO_2yr^{-1} on average for 2001-2023) paired with negligible emissions from deforestation. Both GCB-translated and GFW-translated estimate lower forest removals of -0.05 Gt CO_2yr^{-1} and -0.07 Gt CO_2yr^{-1}, respectively. In Venezuela, all forest land is managed (61 Mha in 2022 in the national inventory document, which is more than the 47 Mha reported to FAO FRA 2020). The large sink in the NGHGI is from the category 'forest land remaining forest land' and includes removals from tree growth in natural forests and plantations. The national inventory document attributes this sink to the implementation of effective conservation and reforestation measures in 65% of the territory under conservation status (Venezuela, 2024). However, the disagreement across datasets (with a larger sink in NGHGI estimates) can most likely be explained by the outdated information used in step 2 of the translation (Figure 1). At the time GCB-translated (Friedlingstein *et al.*, 2025) and GFW-translated (Gibbs *et al.*, 2025) were estimated, the information we had from Venezuela was from pre-Paris reporting (version 1.0 of the NGHGI database; Second National Communication, 2018) where the share of managed forest was not explicitly reported (group A4, Figure 2). Consequently, the masking done in both GCB 2024 and GFW 2024 considers that the majority of the forest area is unmanaged (i.e., intact or primary). If Venezuela's sink (-0.29 Gt CO_2yr^{-1}) is based on all the forest area, this explains most of the discrepancy with GCB/GFW-translated. With the update of information on the area of managed land (i.e., update to decision tree 2.0, and consequent update on the managed forest maps used in the translation), we expect a smaller disagreement across datasets in the next version of the LULUCF Data Hub.

Guyana reports a large forest sink in its NGHGI coupled with negligible deforestation emissions. Both GCB/GFW-translated agree with the low emissions from deforestation but disagree with the large forest sink (Figure 10). The NGHGI reports a forest sink of -0.15 Gt CO_2yr^{-1} (average 2001-2023) which is substantially higher than GCB-translated (-0.02 Gt CO_2yr^{-1}) and GFW-translated (small negligible net sink). Removals from 'land converted to forest land' are not included in the NGHGI and the large sink is due to removals in 'forest land remaining forest land', where removals are estimated for all forest area (18 Mha of forest) with an implied removal factor of -8.3 $tCO_2\ ha^{-1}\ yr^{-1}$. Although this value is very high, it is slightly below of what we here consider as implausible sink. Similarly to Venezuela, also Guyana was allocated in version 1.0 of the NGHGI database to group A4 of the decision tree (unclear use of managed land proxy; Figure 2). In BTR 2024 and corresponding CRT, Guyana explicitly considers all forest managed. With the correction of the temporal mismatch in the information used for the translation, we except a smaller disagreement between GCB/GFW-translated and NGHGI.

For Brazil, fluxes from deforestation are aligned between NGHGI and GCB-original/reclassified and the remaining discrepancies in forest-related fluxes are due to the Forest class. The translation methodology substantially reduces the gap between GCB-translated and NGHGI for the forest class, but the net forest sink in GCB-translated (-0.14 Gt CO_2yr^{-1}) remains below the net forest sink in the NGHGI (-0.31 Gt CO_2yr^{-1}) with a remaining difference of +0.17 Gt CO_2yr^{-1} in GCB-translated compared to NGHGI.

In Mexico, the forest fluxes are larger in the NGHGI (-0.19 Gt CO_2yr^{-1}) than in GCB-translated (-0.09 Gt CO_2yr^{-1}) and GFW-translated (-0.14 Gt CO_2yr^{-1}). While the translation methodology reduces the gap in forest-related fluxes for GCB-translated,

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

the gap slightly increases with the translation of GFW (Figure 10). All forest land is considered managed in the NGHGI corresponding to an area of 95 Mha, and most of the forest fluxes are reported in the category 'forest land remaining forest land'. However, information on the use of the managed land proxy was unclear in the pre-Paris reporting and therefore, in the translation of GCB 2024 (Friedlingstein *et al.*, 2025) and GFW 2024 (Gibbs *et al.*, 2025), Mexico was allocated to group A4 (managed forest not mentioned; Figure 2). Adjusting the alignment (step 2 of the translation methodology) to consider all forest land in Mexico as managed will make the GCB/GFW-translated estimates more similar to the NGHGI. Fluxes from deforestation are similar on average between the three datasets, but trends differ, with the NGHGI estimating a slightly lower and stable deforestation trend, the GCB-original/reclassified a decreasing trend and the GFW-original/reclassified an increasing trend.

3.4.3 South-East Asia region

Larger net sink compared to NGHGI

For forest-related fluxes in the South-East Asia region (Figure 7), no country is identified as a key contributor for the higher net removals than the NGHGI at the global level (Table 5). Both the GCB/GFW-translated estimate a greater net source than the NGHGI for forest and deforestation. Malaysia (in GCB/GFW-translated) and Indonesia (in GCB-translated) have a difference to the NGHGI >0.1 Gt CO_2yr^{-1} (on average for 2001-2023). This difference corresponds to higher emissions, not higher removals, and is therefore discussed below. The exception is on the class Other land uses where Indonesia reports high emissions in the NGHGI (+0.43 Gt CO_2yr^{-1}) compared to the estimates from GCB-original/reclassified (0.04 Gt CO_2yr^{-1}), which contribute to a higher net sink at the global level in GCB-translated.

Larger net source compared to NGHGI

For forest-related fluxes in the South-East Asia region (Figure 7), Malaysia was identified as a key contributing country to the higher net emissions at the global level in both GCB/GFW-translated compared to NGHGI (Table 5; with a difference above 0.1 Gt CO_2yr^{-1}). Indonesia is also a key contributor to higher net emissions at the global level in GCB-translated. Both Malaysia and Indonesia have submitted a BTR in 2024 and the NGHGI database (version 2.0) includes the data provided in the CRTs.
For Malaysia, the higher net removals in GCB/GFW-translated in forest-relates fluxes compared to NGHGI estimates (-0.24 Gt CO_2yr^{-1}) are due to lower forest removals paired with higher deforestation emissions in both GCB/GFW-translated than in the NGHGI (Figure 11). Malaysia considers all forest land as managed (17 Mha) in the NGHGI and reports a net forest sink of -0.24 Gt CO_2yr^{-1}. These large removals are considered implausible in our assessment and are substantially higher than the estimates from the translated GCB and GFW (-0.08 Gt CO_2yr^{-1} and -0.02 Gt CO_2yr^{-1}, respectively). Furthermore, Malaysia does not include emissions from deforestation in the NGHGI, which contrasts with estimates from GCB-original/reclassified (+0.06 Gt CO_2yr^{-1}) and GFW-original/reclassified (+0.18 Gt CO_2yr^{-1}). In a comparison between the GFW model and the NGHGI in Malaysia, Heinrich *et al.* (2023) quantified that 90% of the emissions from deforestation in the GFW model in

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

Malaysia are linked to commodity driven agriculture. The BTR states that all perennial crops, rubber, oil palm, and cocoa are included in the category cropland, and that there was no expansion of croplands from forest land post-1990. This contradiction between datasets can be resolved with stronger collaboration between communities. Malaysia has a strong MRV capacity and tradition in reporting NGHGI to the UNFCCC. A collaboration with the NGHGI team is therefore warranted to better understand how perennial tree crops and transitions between natural forests and tree crops are treated in the NGHGI. In addition, attribution of tree cover loss to a loss of natural forests or management of tree crop plantations is challenging and misclassification errors in EO-based estimates exist (e.g., Tropek *et al.*, 2014).

Indonesia has higher net emissions in forest-related fluxes in the GCB-translated compared to NGHGI. The substantial gap (of +0.55 Gt CO_2yr^{-1}) between the NGHGI estimate (+0.24 Gt CO_2yr^{-1}) and the GCB-original/reclassified estimate (+0.79 Gt CO_2yr^{-1}), is reduced with the translation. The remaining difference of +0.13 Gt CO_2yr^{-1} in GCB-translated compared to NGHGI (Table 5) is mostly due to lower removals in the Forest class. All forest in Indonesia is considered managed (96 Mha) and Indonesia is allocated in group A1 of the decision tree (Figure 2). Emissions from deforestation are consistent between NGHGI and GCB-original/reclassified. For comparisons of forest-related fluxes in Indonesia with the GFW model, these deforestation estimates in the NGHGI and GCB-original/reclassified include CO_2 fluxes from organic soils.

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Preprint. Discussion started: 11 February 2026

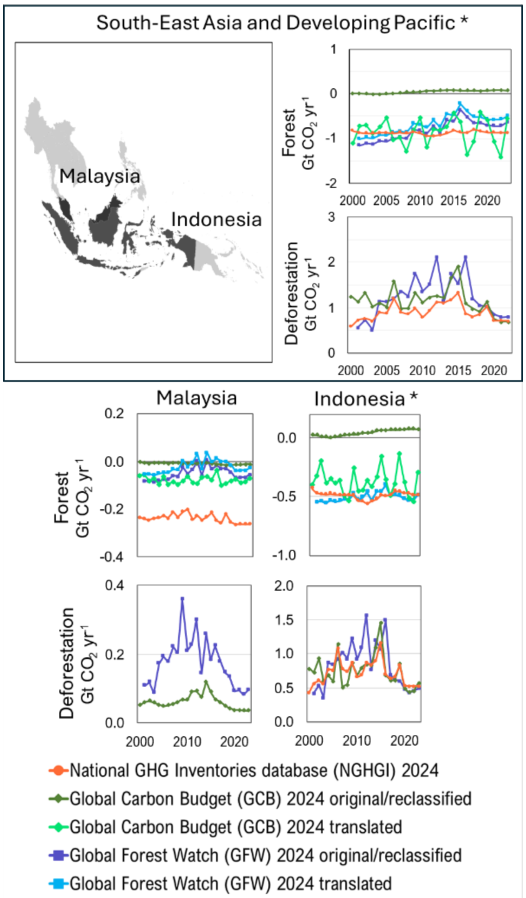

Figure 11. Timeseries for the South-East Asia and Developed Pacific region of annual CO_2 fluxes (2000-2023) for the classes Forest and Deforestation as estimated by: National GHG Inventories database (NGHGI, in orange), Global Carbon Budget 2024 original/reclassified (step 1 in Figure 1) and translated to the NGHGI definition of human-induced CO_2 sink (step 2 in Figure 1; GCB-original/reclassified and GCB-translated in dark and light green, respectively) and Global Forest Watch 2024 in the original version and translated to the NGHGI definitions (GFW-original/reclassified and GFW-translated in dark and light blue, respectively). Timeseries are shown for the whole region and for countries with the largest differences between datasets remain (see Figure 8 and Table 5) – Indonesia, and Malaysia. * For consistency in the comparison with GFW, Deforestation in Indonesia includes emissions from Organic Soils in NGHGI and GCB estimates.

3.4.4. Rest of the World

Larger net sink compared to NGHGI

In the other regions (represented in Figure 7 and not discussed above) differences are less pronounced. However, three countries are also identified as key contributing countries to higher removals in both GCB/GFW-translated compared to NGHGI (with individual differences above ±0.1 Gt $CO_2 yr^{-1}$). For forest-related fluxes, both GCB/GFW-translated show a higher net sink than the NGHGI in Canada, and GFW-translated only estimates a higher net sink compared to NGHGI in Australia and EU27. The NGHGI database version 2.0 uses data from CRTs submitted with the 2024 BTR of Canada, Australia, and of the EU27, the latter as the sum of submissions from EU member states.

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

In Canada, GCB/GFW-translated both consistently show a greater forest sink than NGHGI (Figure 12); approximately -0.30 Gt CO_2yr^{-1} in GCB-translated and -0.22 Gt CO_2yr^{-1} in GFW-translated compared to -0.09 Gt CO_2yr^{-1} in NGHGI (on average 2001-2023). For both NGHGI and GFW-original/reclassified, emissions from deforestation are negligible, and lower than the +0.07 Gt CO_2yr^{-1} estimated by GCB-original/reclassified. Canada reports approximately 60% of forest area as managed (226 Mha managed and 136 Mha unmanaged) and is allocated to the group of countries A2 in the decision tree of Figure 2 ("not all forest is managed, country map available") used to inform the translation (step 2, Figure 1). However, the translation methodology in Canada does not reduce the gap in forest fluxes. In the case of GCB-translated, the translation "over corrects" the GCB-original/reclassified estimate of +0.04 Gt CO_2yr^{-1} on average and increases the gap to NGHGI in the opposite direction (higher sink). Grassi *et al.*, (2021) and Schwingshackl *et al.* (2022) previously noted that the gain-loss method and data used by Canada to estimate forest GHG fluxes imply that the transient impact of recent indirect effects (e.g., CO_2 fertilization etc.) is mostly not captured in GHG estimates and thus the NGHGI estimates closely resemble bookkeeping model estimates for forests (i.e., GCB-original/reclassified). In the GFW model, forest net removals also increase from GFW-original/reclassified (-0.17 Gt CO_2yr^{-1}) to GFW-translated (-0.22 Gt CO_2yr^{-1}) and, therefore, the translation is increasing the gap to the NGHGI. This is likely due to the classification of CO_2 emissions from forest fires in unmanaged lands as natural disturbances rather than anthropogenic fluxes in GFW-translated. In Canada's NGHGI, the GHG emissions and subsequent CO_2 removals from natural disturbances are reported separately as a 'memo item' (or supplementary information) in the CRTs (average of +0.07 Gt CO_2yr^{-1}) and are not included in current versions of the LULUCF Data Hub. Finally, net removals in the Forest class are considerably higher because the Canada's NGHGI 2024 used in V2.0 of our database allocates CO_2 emissions from harvest to the HWP flux rather than to the Forest flux (similarly to the GCB approach).

For EU27, the larger net sink compared to NGHGI in forest-related fluxes is most evident (i.e., above 0.1 Gt CO_2yr^{-1}, on average 2001-2023) in GFW-translated. However, both GCB/GFW-translated indicate a forest sink (-0.52 and -0.68 Gt CO_2yr^{-1}, respectively) that is greater than the aggregated NGHGI of all EU member states (-0.41 Gt CO_2yr^{-1}) (Figure 12). Lower deforestation emissions in GFW contribute to increasing the forest-related higher removals in GFW (Table 5; a -0.30 Gt CO_2 yr^{-1} higher net sink than the NGHGI). The higher forest sink in GFW-translated (corresponding to a -0.27 Gt CO_2yr^{-1} difference on average) and to a lower extent also from GCB-translated (-0.11 Gt CO_2yr^{-1} difference) compared to NGHGI warrants further investigation. Despite the difference in magnitude, all datasets agree on declining forest sinks in EU27, attributed by other research to increased harvest and tree mortality from bark beetle outbreaks and drought (Korosuo *et al.*, 2023; Winkler *et al.*, 2023; Ke *et al.*, 2024; Pan *et al.*, 2024).

In Australia, GFW-translated estimates forest-related net sink of -0.12 Gt CO_2yr^{-1}, which is higher than the close to zero estimate of the NGHGI (Table 5). Similarly to the EU27, in Australia these higher net removals in GFW-translated are due to a combination of higher forest removals (-0.07 Gt CO_2yr^{-1} difference, on average) and lower deforestation emissions (-0.05 Gt CO_2yr^{-1} difference) compared to NGHGI. Australia considers all forest as managed (group A1 in decision tree of Figure 2) but disaggregates the GHG emissions and subsequent CO_2 removals on managed lands that are considered to result from natural

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

disturbances (following the IPCC guidelines; IPCC, 2019) (group B3 in decision tree of Figure 2). Accordingly, fluxes from forest fires are reported separately as a "memo item" in the NGHGI (average of +0.024 Gt CO_2yr^{-1}, from the BTR) and are not included in the current versions of the LULUCF Data Hub. Consequently, the NGHGI shows less inter-annual variability in forest fluxes than GCB and GFW (Figure 12). For example, the peak of emissions in 2019 and subsequent removals in 2020 in GCB-translated and the 2020 peak of emissions in GFW-translated due to a major bushfire in Australia are not reflected in the NGHGI database. The mismatch in the emission spikes between GCB and GFW is likely due to the dependence on satellite acquisition date in the GFW model.

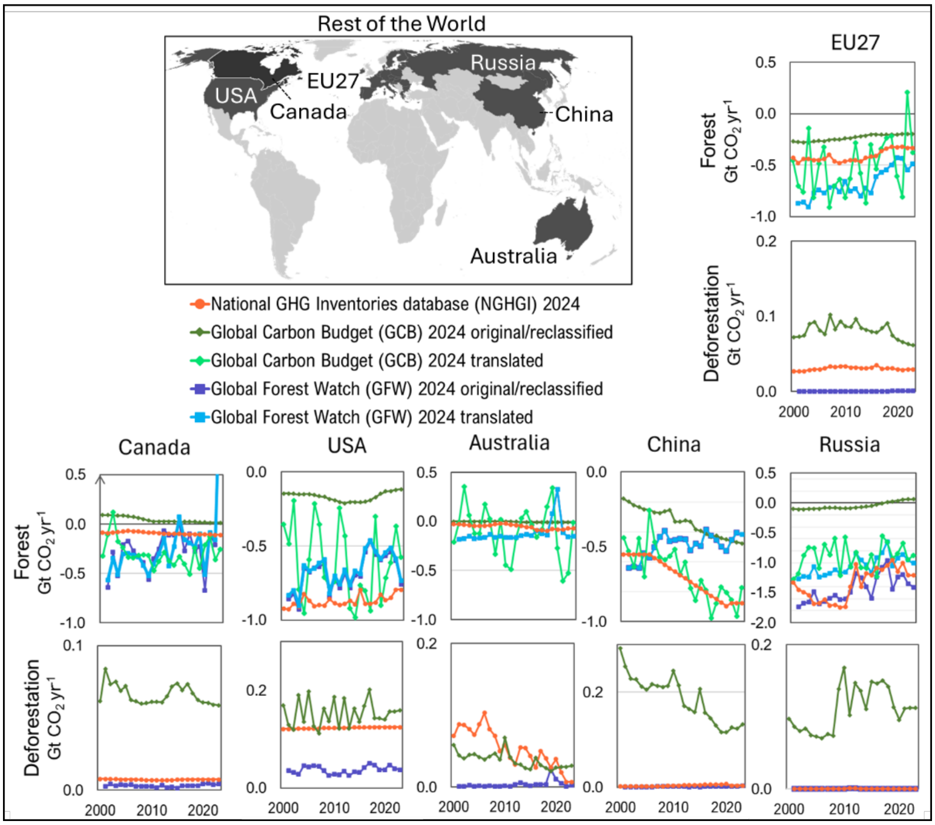

Figure 12. Country examples of annual CO_2 fluxes (2000-2023) for the classes Forest and Deforestation as estimated by: National GHG Inventories database (NGHGI, in orange), Global Carbon Budget 2024 original/reclassified (step 1 in Figure 1) and translated to the NGHGI definition of human-induced CO_2 sink (step 2 in Figure 1; GCB-original/reclassified and GCB-translated in dark and light green, respectively) and Global Forest Watch 2024 in the original version and translated to the NGHGI definitions (GFW-original/reclassified and GFW-translated in dark and light blue, respectively). Timeseries are shown for six countries/Parties with largest differences between datasets in the regions not covered in Figures 9-11 – Australia, Canada, China, EU27, Russia, and USA.

Larger net source compared to NGHGI

In the other regions (represented in Figure 7 and not discussed above), the forest-related larger net source (from higher net emissions or lower net removals) in GCB/GFW-translated compared to the NGHGI is predominant in three countries (with individual differences above ±0.1 Gt CO_2yr^{-1}, on average). Both GCB-translated and GFW-translated show a substantially

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

lower net sink than the NGHGI for Russia, USA and China. In version 2.0 of the LULUCF Data Hub we use data from the CRTs submitted by these three countries with their 2024 BTRs.

In its NGHGI, China reports a large net sink of -0.71 Gt CO_2yr^{-1} (on average 2001-2023) for forest-related land uses (Table 5). For GCB-translated (-0.50 Gt CO_2yr^{-1}) and GFW-translated (-0.49 Gt CO_2yr^{-1}) the estimates are substantially lower. Both GCB/GFW-translated show a higher net source of +0.20 Gt CO_2yr^{-1} compared to the NGHGI, but the similarity in magnitude and sign happens for different reasons. The differences between GCB-translated and NGHGI are mostly driven by different estimates of emissions from deforestation (Figure 12) – negligible in both NGHGI and GFW-original/reclassified, while relatively high in GCB-original/reclassified (+0.18 Gt CO_2yr^{-1}). This substantial gap in deforestation estimates is not addressed in the translation, which focuses mostly on Forest, and suggests that focusing on understanding the underlying reasons for the different estimates in the first step of reallocation of fluxes is essential in future translation efforts. The difference between GFW-translated and NGHGI is in the forest sink, with GFW-translated showing a decreasing trend in the forest sink and a difference in magnitude to NGHGI of +0.26 Gt CO_2yr^{-1} (GFW-translated estimates a sink in the Forest class of -0.49 Gt CO_2yr^{-1}). The translation of the GFW model is not the cause of a larger disagreement because GFW-original/reclassified already estimates a lower forest sink than NGHGI. In contrast, NGHGI and GCB-translated have a good agreement in magnitude (-0.71 Gt CO_2yr^{-1} in NGHGI and -0.68 Gt CO_2yr^{-1} in GCB-translated, resulting in a difference of less than +0.03 Gt CO_2yr^{-1}) and an increasing forest sink. Several studies have found that GCB models underestimate carbon sinks in China. For example, Zhu *et al.* (2025) report a general underestimation, while Schwingshackl *et al.* (2022) attribute the lower sink in GCB-translated compared to NGHGI to CO_2 removals from large-scale afforestation not accounted for by the land-use dataset used by bookkeeping models. However, these two studies use a previous version of GCB land-use data. In GCB 2024, whose results are used here (Friedlingstein *et al.*, 2025), an improved land-use change dataset for China was introduced. As a result, here we do not find an underestimation of the forest sinks between GCB-translated and NGHGI. However, we do still find a substantial gap (above 0.24 Gt CO_2yr^{-1} difference) in Other land uses (Table 5) which will require further investigation in the future.

In Russia, the NGHGI reports a higher forest sink (-1.36 Gt CO_2yr^{-1} on average) than GCB-translated (-0.88 Gt CO_2yr^{-1}) and GFW-translated (-1.05 Gt CO_2yr^{-1}). The sink reported in the latest NGHGI (2024) is twice as large as that reported in NGHGI 2023 due to a recalculation (in version 1.0 of the LULUCF Data Hub, Russia's forest sink is -0.68 Gt CO_2yr^{-1} on average. Similarly to China, emissions from deforestation are almost negligible in both NGHGI and GFW-original/reclassified, while they are relatively high in GCB-original/reclassified (+0.10 Gt CO_2yr^{-1}). As for China, the differences in deforestation estimates in Russia underscore the importance of examining input data and focusing on the first step of the translation to understand the differences and improve the conceptual consistency of the datasets. Forest fluxes in NGHGI seem to align better in magnitude and trend with GFW-original/reclassified and with inverse model estimates filtered for the area of managed forest (Deng *et al.*, 2025). Removing sinks from unmanaged forests in GFW-translated increases the gap in the forest fluxes to NGHGI instead of reducing it (from a difference of -0.08 Gt CO_2yr^{-1} in GFW-original/reclassified to a difference of +0.31 Gt CO_2yr^{-1}). Future work may include revisiting the use of non-intact forest as proxy maps of managed forest use and ideally

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

use country-based maps. For forest-related fluxes, the gap between GCB-translated and NGHGI is still substantial (+0.59 Gt CO_2yr^{-1}, on average), through a combination of higher emissions from deforestation (+0.10 Gt CO_2yr^{-1}) and lower removals from forest (+0.48 Gt CO_2yr^{-1}). Although a larger sink obtained from the use of newer inventory data in the 2024 NGHGI was expected to the reduce the existing discrepancies between GCB-translated and previous NGHGI from Russia (Schwingshackl *et al.*, 2022), we find that the recalculation is actually increasing the gap.

In the USA, both GCB-translated (-0.63 Gt CO_2yr^{-1}) and GFW-translated (-0.66 Gt CO_2yr^{-1}) report lower forest removals than NGHGI (-0.87 Gt CO_2yr^{-1}), resulting in a difference of +0.24 Gt CO_2yr^{-1} in GCB-translated and +0.21 Gt CO_2yr^{-1} in GFW-translated than NGHGI estimates. In addition, emissions from deforestation are slightly higher in GCB-original/reclassified than the NGHGI, while in GFW-original/reclassified emissions from deforestation are lower. Consequently, the gap between GCB-translated and NGHGI for forest-related fluxes is larger (+0.27 Gt CO_2yr^{-1} difference) than the gap between GFW-translated and NGHGI (+0.12 Gt CO_2yr^{-1} difference). In the USA almost all forest area is considered managed (281 Mha of managed forest and 10 Mha unmanaged). As already noted by Schwingshackl *et al.* (2022), GCB-translated estimates lower removal in Other land uses compared to NGHGI (a difference of +0.09 Gt CO_2yr^{-1}), which is primarily attributable to removals from trees in settlements in the NGHGI not included in GCB data. Here we note an additional and even larger discrepancy in the Forest class (corresponding to +0.24 Gt CO_2yr^{-1}) that we cannot immediately explain.

3.4.4. Synthesis of country-level findings

Despite the overall convergence achieved through the translation, important country-level differences exist. The country-level discussions presented in the previous sections highlights cases contributing to a remaining gap after translation. Here, we summarise the main findings emerging from those examples.

Common reasons emerge across regions and countries that explain the lower net LULUCF sink in GCB-translated compared to NGHGI. Such reasons can include i) larger emissions from deforestation (China, Russia, Malaysia, Canada, and EU27) estimated by GCB-translated compared to NGHGI, which aggregated correspond to a 0.45 Gt CO_2yr^{-1} larger source in GCB-translated; and ii) lower forest sinks due to ii.a) implausible forest sinks in NGHGI (Mali, Malaysia, and Namibia), which amounts to about -0.60 Gt CO_2yr^{-1} globally, or ii.b) inaccurate translation due to the temporal mismatch in the information flow on the use of the managed land proxy (Guyana, Venezuela, Mexico), which can partly explain a lower sink of 0.51 Gt CO_2yr^{-1} in GCB-translated compared to NGHGI for the sum of these three countries.

In GFW-translated, both the implausible forest sinks in the above-mentioned countries and the translation inaccuracies (Guyana, and Venezuela), contribute to lower sink in forest-related land-uses compared to NGHGI. However, this lower sink is compensated by larger net sink estimates in other countries, resulting from inaccuracies in the information on the use of the managed land proxy (Argentina and Colombia), from incomplete reporting (Angola, Nigeria, Colombia), and from lower emissions from deforestation in GFW compared to NGHGI (DRC, Cote d'Ivoire, Angola, Argentina, Venezuela, Malaysia, USA, Australia, and Nigeria, aggregating to a 0.86 Gt CO_2yr^{-1}). Incomplete or inaccurate NGHGI estimates (DRC and Angola

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

have not yet submitted a BTR, and Nigeria does not fully report removals), can explain part of these differences. However, large discrepancies persist even for countries with robust data and long-standing NGHGI experience such as the EU27 and Russia.

In some case, the difference between models and NGHGI is partly due to a different treatment of natural disturbances (Canada, Australia) and HWP (Canada). The differences above will be prioritized in future work.

3.5 Updates of the LULUCF Data Hub and future work

With each version of the LULUCF Data Hub we anticipate more disaggregated, accurate and complete NGHGI data, especially in terms of land use and time series coverage from developing countries, as well as recalculations in NGHGI from developed countries (Figure 4). Updates in global carbon cycle model estimates – such as model improvements or updates in the land-use activity data or forcing – and in EO-based datasets will also be incorporated as they become available. In this study we illustrate the potential of the LULUCF Data Hub to facilitate the communication between communities (NGHGI, global carbon cycle models and Global EO) and plan future steps as we move forward in the translation efforts.

Here we show results from version 2.0 of the LULUCF Data Hub which includes NGHGI data from 2024 (NGHGI database version 2.0) and a comparison with data from GCB 2024 and GFW 2024 in the two steps of the translation process (original/reclassified and translated, see Figure 1). All versions will remain available in the LULUCF Data Hub (and online repository) to show how estimates from the different communities evolve over time. Annual updates are planned, with the release of one new version per year. For example, version 2.0 includes NGHGI submitted in 2024 (NGHGI database 2.0), GCB 2024, GFW 2024. Version 3 shall include NGHGI submitted in 2025, GCB 2025, GFW model 2025, and other emergent datasets that meet the LULUCF Data Hub eligibility (see section 2.5; for example, top-down approaches using atmospheric inversions). To achieve a compromise between timeliness and different release dates of datasets, version 3.0 was released earlier in the year (in June 2025) with NGHGI 2025 data (NGHGI for Annex I countries are submitted every year around April). It is desirable to have the latest NGHGI data available sooner because it informs the translation to NGHGI definitions in the other datasets (Figure 1), namely the managed land proxy map (described in section 2.2), the conceptual alignment with NGHGI in the new cycle of GCB (section 2.3) and in the new cycle of the GFW model (section 2.3). Version 3.0 in the LULUCF Data Hub will be replaced by version 3.1 with the GCB 2025 and GFW 2025 in late 2025 when both those datasets become publicly available. In subsequent years, the updates will follow the same approach: one new version with the annual NGHGI data mid-year, to be replaced at the end of the year with the updates from global datasets.

With the planned schedule for data updates, the inaccuracies from the translation due to a time mismatch in the use of managed land proxy information will be fixed in future translations of GCB/GFW data. In addition to data updates, expected expansions to the LULUCF Data Hub include: i) adding land-related non-CO_2 emissions (separately and combined with CO_2 fluxes), ii) adding CO_2 fluxes from natural disturbances reported separately by some countries in “memo item”, and from other datasets in the LULUCF Data Hub as appropriate, iii) display NGHGI data clearly identifying gap-filled and not gap-filled annual data.

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

While this study does not attempt a full comparison of uncertainties across datasets – given their diverse methodologies and definitions – future developments of the Data Hub could also explore ways to more explicitly communicate the range of uncertainties alongside the flux estimates, complementing the convergence-across-datasets approach adopted here. Areas where we expect to increase clarity and comparability across datasets include shifting agriculture and HWP.

This study confirms the need to investigate persistent differences between NGHGI and independent data at the country level to understand the reasons behind these differences and to refine translation methodologies as needed. Recent studies have already begun addressing this need (Schwingshackl *et al.*, 2022; Heinrich *et al.*, 2023; Deng *et al.*, 2025; Poulter *et al.*, 2025), offering valuable insights into how countries implement the IPCC guidelines in their NGHGI according to their national circumstances. Next steps include i) strengthening the engagement with NGHGI specialists to improve the transparency of NGHGI data in the LULUCF Data Hub in cases where we are currently making assumptions (e.g., use of managed land proxy, allocation of fluxes from IPCC categories to subcategories), and to secure their support in using the datahub to facilitate communication of NGHGI country data to the other communities; ii) work collaboratively across communities on specific country cases to understand the reasons behind persisting disparities in the estimates; iii) promote the use of the LULUCF Data Hub as a potential tool for quality control (e.g., in the review of NGHGI under the UNFCCC) and to share the implications of the translation with a wider audience.

4 Data Availability

The data from this study can be visualized and downloaded from the LULUCF Data Hub hosted by the European Union Forest Observatory (https://forest-observatory.ec.europa.eu/carbon) and as bulk download from the online repository (Melo *et al.*, 2025; available at https://doi.org/10.5281/zenodo.17140775). The data in this study correspond to version 2.0 of the LULUCF Data Hub (Melo *et al.*, 2025b; available at https://doi.org/10.5281/zenodo.17151515). Past and subsequent versions of the datasets in the LULUCF Data Hub will remain available in the same platforms.

5 Conclusions

In recent years, the modelling and GHG inventories communities have engaged in in-depth discussions to understand the differences between estimates of land use fluxes at global level. Following the recommendation of the IPCC expert meeting on land (IPCC, 2024), the outline of the IPCC 7th Assessment Report indicated that historical estimates and scenarios for anthropogenic land-based CO_2 fluxes shall be consistent with national inventory definitions (Grassi *et al.*, 2025). To support the "translation" efforts (i.e., conceptually align estimates from various datasets), this study presents the LULUCF Data Hub, a living data platform designed to foster dialogue across communities and enhance transparency and comparability of global and country-level anthropogenic land-based CO_2 flux estimates. We provide updated data from NGHGI submitted to the UNFCCC (as of April 2025; corresponding to version 2.0 of the LULUCF Data Hub) and present the efforts from the global

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

carbon cycle modelling and Earth observation communities to translate their land-use CO_2 flux datasets with the NGHGI definitions, demonstrating the progress made since the IPCC 6th Assessment Report (IPCC, 2023) and supporting the work for the IPCC 7th Assessment Report.

Our results show general convergence in average flux estimates across translated (or conceptually aligned) datasets. NGHGI data indicate a net global LULUCF sink of -3.4 Gt CO_2yr^{-1} averaged over the period 2001–2023, including a global sink of -3.2 Gt CO_2yr^{-1} for forest-related land uses (sum of CO_2 fluxes from forest and deforestation partially including emissions from organic soils). The gap in LULUCF between GCB and NGHGI is reduced from +8.1 to +1.8 Gt CO_2yr^{-1} when considering natural sinks in managed forests (where a positive gap indicates higher net emissions or lower removals in the global dataset compared to NGHGI, and a negative gap indicates lower net emissions or higher removals). In forest-related fluxes, the translation reduces the gap to NGHGI estimates from +7.1 to -0.7 Gt CO_2yr^{-1} in GCB and from -2.7 to -0.3 Gt CO_2yr^{-1} in GFW. The gap in forest-related land use CO_2 flux estimates between GCB and GFW is reduced from +9.7 to +1.0 Gt CO_2yr^{-1}.

However, the good agreement on the magnitude of global land use CO_2 fluxes does not always reflect a genuine reconciliation of the differences for individual countries. Regional variations and country-level discrepancies persist, with global datasets estimating higher net removals (or lower net emissions) compared to NGHGI in some countries, which are largely balanced out by estimates of higher net emissions (or lower removals) in other countries. On the one hand, the translated global datasets estimate higher net removals (or lower net emissions) compared to NGHGI in 75 (for GCB) and 101 (for GFW) countries, corresponding to a larger sink of -2.5 Gt CO_2yr^{-1} in GCB and -3.0 Gt CO_2yr^{-1} in GFW. Key contributors (i.e., countries showing average absolute differences > 0.1 Gt CO_2yr^{-1}) are: Nigeria, DRC, Cote d'Ivoire, Angola, and Canada in both datasets (GCB and GFW); Colombia only in GCB, and Brazil, Argentina, Australia, and EU27 only in GFW. On the other hand, the translated GCB and GFW estimate higher net emissions (or lower net removals) compared to NGHGI in the remaining countries (n=105 for GCB and n=80 for GFW) totalling +2.1 Gt CO_2yr^{-1} in GCB-translated and +1.9 Gt CO_2yr^{-1} in GFW-translated compared to NGHGI estimates. Key contributors to higher net emissions (or lower net removals; absolute differences > 0.1 Gt CO_2yr^{-1}) are: Russia, Malaysia, Venezuela, USA, China, Mali, Guyana, and Namibia in both datasets, Brazil, Indonesia, and Mexico only in GCB, and no countries only in GFW. Divergence between data sources in forest and deforestation net emissions trends for 2001–2023 is noticeable in developing countries (e.g., China, DRC) and especially in the forest sinks of the African region (e.g., DRC, Nigeria, Cote d'Ivoire and Angola), where GCB-translated indicates a pronounced increasing forest sink, the NGHGI a stable or slightly decreasing sink, and GFW-translated a markedly decreasing sink. Conversely, the three datasets agree on declining forest sinks in the EU27 and Russia.

Our findings confirm the need for additional, detailed country-specific investigations to understand the reasons behind the differences after comparison with GCB-translated and GFW-translated, and support continued methodological refinements, as has already been started here and by others (Schwingshackl *et al.*, 2022; Heinrich *et al.*, 2023). We show that differences can still be disturbingly large, also in well studied countries, or in countries that are data rich and have well-established NGHGIs. The LULUCF Data Hub builds on existing information and outlines where more targeted future research is needed by

https://doi.org/10.5194/essd-2025-631
Preprint. Discussion started: 11 February 2026

identifying countries i) where NGHGI estimates differ the most from translated GCB and GFW data, ii) where current translation methodologies are not sufficient to explain the observed gaps, and iii) where trends across datasets diverge the most. These countries may serve as initial candidates for the third cycle of the REgional Carbon Cycle Assessment and Processes Study (RECCAP3) initiative under the Global Carbon Project, which will increasingly focus on national budgets (Canadell *et al.*, 2025), in synergy with efforts under the IPCC Task Force on GHG inventories and the Global Forest Observations Initiative (GFOI) to enhance collaboration between communities.

As we move forward in the reconciliation efforts through the proposed translation methodology and in disseminating the results of these endeavours, it is also crucial that the implications of translating the global modelling estimates into the national inventory definitions are clearly communicated to policymakers and reflected in national targets (Grassi *et al.*, 2025), to avoid the undesired outcome of land sinks invertedly diluting ambition for stabilizing global temperatures. Ultimately, all these efforts will enable a more consistent and credible assessment of the role of land use in climate mitigation progress at both global and country levels, which is essential in the context of the next IPCC Assessment Reports and the next Paris Agreement's Global Stocktake, while also providing a common dataset across IPCC Working Groups to better connect mitigation with adaptation.

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