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Carbon fluxes from land 2000-2020: bringing clarity on countries' reporting

Giacomo Grassi[1]*, Giulia Conchedda[2], Sandro Federici[3], Raul Abad Viñas[1], Anu Korosuo[1], Joana Melo[4], Simone Rossi[5], Marieke Sandker[6], Zoltan Somogyi[7], Francesco N. Tubiello[2]

1 Joint Research Centre (JRC), European Commission, Ispra, 21027, Italy.

2 Statistics Division, FAO, Rome, 00153, Italy

3 Institute for Global Environmental Strategies, IGES, Hayama, 240-0112, Japan

4 School of Geography, University of Leeds, Leeds, LS2 9JT, UK

5 Joint Research Centre (JRC) Consultant, ARCADIA SIT s.r.l., Vigevano (PV), 27029, Italy

6 Forestry Division, FAO, Rome, 00153, Italy

7 University of Sopron, Forest Research Institute, Sopron, H-9400, Hungary

Correspondence to: Giacomo Grassi (giacomo.grassi@ec.europa.eu)

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Abstract

Despite an increasing attention on the role of land in meeting countries' climate pledges under the Paris Agreement, the range of estimates of carbon fluxes from Land Use, Land-Use Change and Forestry (LULUCF) in available databases is very large. A good understanding of the LULUCF data reported by countries under the United Nations Framework Convention on Climate Change (UNFCCC) - and of the differences with other datasets based on country reported data - is crucial to increase confidence in land-based climate change mitigation efforts.

Here we present a new data compilation of LULUCF fluxes of carbon dioxide (CO_2) on managed land, aiming at providing a consolidated view on the subject. Our database builds on a detailed analysis of data from National Greenhouse Gas Inventories (NGHGIs) communicated via a range of country reports to the UNFCCC, which report anthropogenic emissions and removals based on the IPCC (Intergovernmental Panel on Climate Change) methodology. Specifically, for Annex I countries, data are sourced from annual GHG inventories. For non-Annex I countries, we compiled the most recent and complete information from different sources, including National Communications, Biennial Update Reports, submissions to the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) framework and Nationally Determined Contributions. The data are disaggregated into fluxes from forest land, deforestation, organic soils and other sources (including non-forest land uses). The CO_2 flux database is complemented by information on managed and unmanaged forest area as available in NGHGIs. To ensure completeness of time series, we filled the gaps without altering the levels and trends of the country reported data. Expert judgement was applied in a few cases when data inconsistencies existed.

Results indicate a mean net global sink of -1.6 Gt CO_2/yr over the period 2000-2020, largely determined by a sink on forest land (-6.4 Gt CO_2/yr), followed by source from deforestation (+4.4 Gt CO_2/yr) and minor fluxes from organic soils (+0.9 Gt CO_2/yr) and other land uses (-0.6 Gt CO_2/yr).

Furthermore, we compare our NGHGI database with two other sets of country-based data: those included in the UNFCCC GHG data interface, and those based on forest resources data reported by countries to FAO and used as inputs into estimates of GHG emissions in FAOSTAT. The first dataset, once gap-filled as in our study, results in a net global LULUCF sink of -5.4 Gt CO_2/yr. The difference with the NGHGI database is in this case mostly explained by more updated and comprehensive data in our compilation for non-Annex I countries. The FAOSTAT GHG dataset instead estimates a net global LULUCF source of +1.1 Gt CO_2/yr. In this case, most

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of the difference to our results is due to a much greater forest sink for non-Annex I countries in the NGHGI database than in FAOSTAT. The difference between these datasets can be mostly explained by a more complete coverage in the NGHGI database, including for non-biomass carbon pools and non-forest land uses, and by different underlying data on forest land. The latter reflects the different scopes of the country reporting to FAO, which focuses on area and biomass, and to UNFCCC, which explicitly focuses on carbon fluxes. Bearing in mind the respective strengths and weaknesses, both our NGHGI database and FAO offer a fundamental, yet incomplete, source of information on carbon-related variables for the scientific and policy communities, including under the Global Stocktake.

Overall, while the quality and quantity of the LULUCF data submitted by countries to the UNFCCC significantly improved in recent years, important gaps still remain. Most developing countries still do not explicitly separate managed vs. unmanaged forest land, a few report implausibly high forest sinks, and several report incomplete estimates. With these limits in mind, the NGHGI database presented here represents the most up-to-date and complete compilation of LULUCF data based on country submissions to UNFCCC.

Data from this study are openly available via the Zenodo portal (Grassi et al. 2022), at https://doi.org/10.5281/zenodo.6390739.

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1. Introduction

Land-based mitigation is increasingly recognized as a key strategy to reach the Paris Agreement's aim to "achieve a balance between anthropogenic emissions by sources and removals by sinks". Global models indicate that changes in land-use and land management contribute to around 12% of the total global anthropogenic CO_2 emissions (Friedlingstein et al. 2021), mainly through deforestation. Simultaneously, land uses, particularly forests, may contribute to climate change mitigation through carbon absorption (sink) and storage (stock) in biomass, dead organic matter, soil, and wood products.

Despite an increasing attention to the Land Use, Land-Use Change and Forestry (LULUCF) sector under the United Nations Framework Convention on Climate Change (UNFCCC), including nature-based solutions to reduce CO_2 emissions and enhance CO_2 removals (e.g. Griscom et al. 2017, Roe et al. 2021), notable differences still exist among global land-related datasets, in both the magnitude of the net CO_2 flux and its trend (IPCC 2019, Harris et al. 2021, Grassi et al. 2021, Friedlingstein et al. 2021, Deng et al. 2022, Feng et al. 2022). These differences cause concern because, if not explained, they may jeopardize the confidence in LULUCF to achieve climate change mitigation.

Previous studies (Grassi et al. 2018, 2021) have analyzed the reasons for large differences in land use CO_2 fluxes - globally in the order of billion tonnes (Gt) of CO_2 per year - between the country submissions to UNFCCC and global models (IPCC 2019, Friedlingstein et al. 2021). There, the differences were found to be mostly due to different approaches to assess the anthropogenic forest sink.

However, while of a similar order of magnitude, less attention has been paid to differences between various country submissions to UNFCCC, the different collections of UNFCCC country data (e.g. Grassi et al. 2021 vs. The Washington Post 2021) and other LULUCF datasets such as FAOSTAT (Tubiello et al. 2022). These differences are due to three main factors.

First, it is arduous to collect LULUCF carbon flux information from some reports that countries submit to the UNFCCC, which here we broadly define as National Greenhouse Gas Inventories (NGHGIs). While data from Annex I (AI) countries are straightforward to retrieve because they are organized in annually submitted standardized tables within the GHG inventories (GHGIs), Non-Annex I (NAI) countries submit their NGHGI information less regularly, not in a standardized format, and in a number of reports of different scope and objectives: the National Communications (NCs), the Biennial Update Reports (BURs), submissions under the

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REDD+ (Reducing Emissions from Deforestation and forest Degradation, and the conservation and enhancement of forest carbon stocks) framework and the Nationally Determined Contributions (NDCs). This highly heterogeneous and fragmented reporting makes it very difficult to identify and assess LULUCF data for NAI countries.

Second, different LULUCF datasets – and sometimes also different country submissions to the UNFCCC – report emissions and removals at different levels of aggregation of land uses, carbon pools and gases. This, together with differences in methodological approaches, makes the comparisons between the datasets difficult.

Third, carbon fluxes are associated with complex and highly dynamic biological systems, which are further affected by various natural and anthropogenic drivers. Estimating these fluxes in a complete, accurate and consistent manner is very difficult.

While dealing with and finding solutions to the third factor is crucial to further improve LULUCF estimates, minimising the 'noise' and the bias that the first two factors often introduce is equally important. In other words, before comparing country reported LULUCF data with other LULUCF datasets, one should first ask: Am I using the most appropriate country data? Am I comparing apples to apples?

From the end of 2024, under the Enhanced Transparency Framework package finalised at COP26 (https://unfccc.int/enhanced-transparency-framework), all UNFCCC Parties will start reporting with a harmonized format. This will happen through Biennial Transparency Reports (BTRs) that will include, among other things, (i) a national inventory report of anthropogenic emissions and removals, consisting of a national inventory document (with a description of the methods used) and common reporting tables (noting that AI Parties will continue to provide flux estimates on a yearly basis), and (ii) information to track progress towards targets as defined in the NDC. This harmonized reporting is expected to alleviate many of the concerns discussed above.

However, we cannot wait until the end of 2024 to get the needed information. Notably, the first Global Stocktake under the Paris Agreement will take place in 2022-2023, aimed at assessing the countries' collective progress towards meeting the long-term goals of the Paris Agreement. The Global Stocktake is a crucial step, because any identified gap between the globally aggregated country emissions (reported and pledged) and emission pathways consistent with the Paris Agreement is expected to motivate increased mitigation ambition in subsequent NDCs. Since historical progress in the implementation of pledges will be monitored through NGHGIs, confidence on NGHGIs is crucial because "If you can't measure it, you can't improve it".

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In this context, a better understanding of the LULUCF data that countries report to the UNFCCC, and of the differences with other relevant country-based datasets, is important to the global assessment of climate efforts and, more broadly, to increase confidence on land-related climate change mitigation.

In this study, we collected LULUCF CO_2 flux data from AI countries' GHG inventories and from the most recent and complete NAI countries' reports to the UNFCCC (i.e., NCs, BURs, REDD+ and NDCs), complemented by any available information on managed and unmanaged forest area. To ensure a complete time series 2000-2020, we filled the gaps using standard statistical methods, with the aim to maintain the levels and trends of the underlying, reported raw data. Data are disaggregated into fluxes from forest land (including harvested wood products), deforestation, organic soils and other fluxes (including non-forest land uses).

The objectives of this study are therefore as follows: (i) to present a comprehensive and updated collection of carbon flux data from the most recent and complete country reports to the UNFCCC (i.e. the 'NGHGI database', NGHGI DB), which can be used by the scientific and policy communities; (ii) to assess the scale and understand the reasons for the discrepancies among different collections of UNFCCC country data, i.e. our NGHGI DB and the UNFCCC Greenhouse Gas Data Interface (GHGDI); (iii) to assess the scale and understand the reasons for the differences between our NGHGI DB and the FAOSTAT LULUCF emissions estimates, which represent an alternative, independent source of data based on country reporting to FAO FAO's Global Forest Resources Assessment 2020 (FAO, 2020a; FAO 2020b).

2. Methods

2.1 The NGHGI LULUCF database (NGHGI DB)

In this study, we use the term National GreenHouse Gas Inventories (NGHGIs) in a broad sense, including anthropogenic GHG data submitted to UNFCCC through any official country report. The data in such reporting processes are estimated using one of the relevant IPCC Guidelines (IPCC, 1996, 2006, 2019). Although the Paris Agreement removes the previous distinction between Annex I (AI) and non-Annex I (NAI) countries in terms of targets and reporting (retaining some flexibility in GHG reporting for developing countries), we use this distinction here because it still reflects relevant differences in historical GHG data.

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The NGHGI LULUCF database presented here (NGHGI DB) is a significant update to data in Grassi et al. 2021, including more recent data (until February 2022), greater coverage of countries, more disaggregated categories and additional methodological information.

Data were compiled from various submissions to UNFCCC (Table 1), prioritising the most recent one but also taking the completeness of information into account. For AI countries, all information is sourced from the GHGI. For NAI countries, NC/BUR, REDD+ and NDC submissions have been used. For each country, only one type of submission is used in the NGHGI DB. Expert judgement is applied in a few cases, e.g. if a NC/BUR is clearly more complete than a slightly more recent NDC, the former is used (see country-specific explanation in the Supplementary Table 1). In most cases, these exceptions have little or no influence on the carbon fluxes, with the notable exception of the Central African Republic. In this case, we considered the forest sink reported in the most recent country submission (NDC 2021) to be biophysically impossible (-0.7 Gt CO_2/yr over 20 Mha of forest, equivalent to an area-specific sink of some 35 tCO_2/ha*yr), and used the NDC 2016 instead (forest sink of -0.3 Gt CO_2/yr).

Since UNFCCC data for years prior to 2000 are less frequent and less reliable for most NAI countries, our NGHGI DB includes only post-2000 data.

While AI countries report a complete time series, for most NAI countries some gap-filling was necessary to overcome a lack of data for all years. Gap-filling was applied through linear interpolation between two points and/or through extrapolation backward (till 2000) and forward (till 2020) using the single closest available data (Supplementary Tables 4 and 5 show the original and gap-filled time series, respectively). The overall gap-filling rate was 47% (5% for AI and 60% for NAI countries), calculated by dividing the number of gap-filled data by the total number of yearly values in the database for all the 195 countries. When normalized by the contribution to the global carbon flux values, the gap-filling rate was 32% (5% for AI and 42% for NAI countries) of the absolute total flux (calculated by summing the absolute fluxes of the single land categories used here; forest land, deforestation, organic soils, other land uses). This indicates that most of the NAI countries where the biggest fluxes occur reported relatively complete time series.

Furthermore, we tested the potential impact of different gap-filling methods on the level and trends of carbon fluxes. Specifically, we compared the procedure described above with two alternative approaches: (i) i.e. the average 2000-2020 using the non-gap-filled data, and (ii) a gap filling where the interpolation between two

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data is done taking the most recent data to fill the missing years (while extrapolation backward and forward is done as described above).

It is worth noting that, for NAI countries, NC/BUR, REDD+ and NDC submissions differ in scope and objectives (Table 1). Both NCs and BURs include a GHG inventory section, concern land-based reporting, aim to include all land uses, carbon pools and gases, and to systematically neither over- nor underestimate emissions/removals (which means accuracy of estimates is in principle achieved). While NCs are typically submitted every four years, BURs provide an update of the information presented in NCs, typically every two years. Reporting modalities are found in Annex III to, Decision 2/CP17 and in Decision 17/CP8 and respectively. The methods used (i.e. 1996 or 2006 IPCC Guidelines), the amount of information and the disaggregation of the categories reported varies considerably among countries.

The REDD+ reporting is voluntary, with the objective of receiving results-based payments. Reporting tends to be activity-based, and is rarely complete: 87% of reporting countries cover the entire national territory, 42% include both emissions and removals from forest land and conversions to and from forest land (i.e., deforestation, forest degradation and enhancement of forest-carbon stock), 24% cover all gases and only 7% cover all carbon pools. The 2006 IPCC Guidelines are typically used. Generally, a large amount of methodological information is provided, which is technically assessed by a team of independent UNFCCC experts.

The NDCs outline the post-2020 efforts by each country to reduce national emissions and adapt to the impacts of climate change, as requested by the Paris Agreement. While the focus is on the future actions, historical emissions and removals from LULUCF are sometimes included, although typically with little or no methodological information and at a rather aggregated level.

Table 1.

Data from this study are openly available via the Zenodo portal (Grassi et al. 2022) at https://doi.org/10.5281/zenodo.6390739

2.2 Area of Managed Land

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The NGHGI data submitted to UNFCCC are expected to use, as default, the 'managed land' proxy following the 2003 IPCC GPG for LULUCF and the subsequent IPCC Guidelines (IPCC 2006, 2019), according to which all GHG fluxes from managed land areas are considered 'anthropogenic', while GHG fluxes on unmanaged land areas are not estimated. Only a minority of countries explicitly reported information on the implementation of this proxy (Ogle et al. 2018, Grassi et al. 2021). For the rest, we considered that the managed land proxy is implicitly used in all other country reports to the UNFCCC, which means that information reported is sourced from managed land only.

Most AI countries consider their whole land surface as managed, though some countries (for example, the United States, Canada and Russia) specifically report the area of unmanaged lands (for forest land, grassland and wetlands).

By contrast, the vast majority of NAI countries do not distinguish between managed and unmanaged areas, with few not even reporting forest area extent. When the information of forest area was available in the NGHGIs, we considered this area as managed, whenever it can be assumed that it is the area over which the GHG emissions are estimated. Where this information is not available, we used the area of secondary forests and plantations from country reports to the FAO Forest Resources Assessment, (FRA; FAO, 2020) as a proxy managed forest (see Supplementary Table 2). In total, the amount of area from FRA that was used to gap-fill the missing information from NGHGIs amounts to 46 Mha (1% of total forest area from NGHGIs).

2.3 CO_2 Fluxes

The LULUCF CO_2 fluxes in the NGHGI DB are disaggregated into the following categories: Forest land (FL, including harvested wood products, excluding organic soils), Deforestation (forest converted to other land uses), Organic soils (including organic soils from all land uses and peat fires) and Other land uses (including cropland, grassland, wetlands, settlements, other land), following the mapping of Table 2. When possible, data on FL were further split in the two subcomponents forest land remaining forest and (FL-FL, i.e. forests existing from 20 years or more) and land converted to forest land (L-FL, i.e. forest established less than 20 years ago). While data on FL and Deforestation (typically the most important categories) are available for most countries, data for Organic soils and Other are available for most AI countries only but only for some NAI countries (usually the largest in terms of area, Supplementary Table 2). For those NAI countries still using the categories of the Revised 1996 IPCC Guidelines, the mapping to the categories above is described in Table 2. The

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categories used in our NGHGI DB represent a compromise between very disaggregated information from some countries (typically AI and a few NAI countries) and very aggregated one from others. In a few cases - generally for relatively small NAI countries -, our categorization required some approximation: for example, where the country reported only "AFOLU net CO_2 flux" or "LULUCF net CO_2 flux", the flux was assigned to FL where it is a net removal, and to Deforestation where it is a net emission (Table 2). This is justified by the fact that, when a more disaggregated reporting is available, the vast majority of the CO_2 removals occur in FL and the vast majority of the CO_2 emissions are associated with deforestation.

Although most NGHGIs include reporting for all GHGs, in this study we consider only CO_2. Exceptions are some NAI countries for which it was not possible to separate CO_2 from non-CO_2 emissions (mainly CH_4 and N_2O from forest fires). However, based on information available from AI countries and the largest NAI countries - for which non-CO_2 emissions are around 6% of the total CO_2-equivalent LULUCF flux - the global contribution of non-CO_2 emissions in our NGHGI DB (i.e. from NAI countries that do not separate GHGs) is assumed be negligible.

In terms of carbon pools, FL and Deforestation data always include above- and below-ground biomass; data for the other carbon pools (dead organic matter, mineral soils, harvested wood products) are only reported by Annex I countries and by the largest NAI countries (including Brazil, China, India, Indonesia, Mexico).

For the purpose of our analysis, we considered "implausible" those reported forest sinks implying average sequestration rates greater than -10 tCO_2/ha*yr (if occurring over >1Mha). This threshold has been selected for indicative purposes, on the basis of the distribution of this parameter among countries (see Supplementary Figure 1), the typical range of IPCC default factors and expert judgement. Five countries were included in this category (with a forest sink between -14 tCO_2/ha*yr and -18 tCO_2/ha*yr), collectively covering about 70 Mha of forest: Central African Republic (using the NDC 2016), Mali, Namibia, Malaysia and Philippines. For these countries, data are included in the NGHGI DB but are considered separately in the discussion (i.e. numbers are considered very unlikely, but not impossible). It is to be noted that we did not apply an analogous method for screening countries which might overestimate gross emissions and/or underestimate gross or removals. Also, if a country is not filtered out by the above threshold does not mean that its forest sink estimates are necessarily accurate.

Table 2.

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2.4 Uncertainties

Grassi et al. 2017 collected values of uncertainty for the LULUCF sector based on information from country reports to UNFCCC (see the Supplementary Information of Grassi et al. 2017). Overall, when the information above is complemented by expert judgement (Grassi et al. 2021), the uncertainty on the net LULUCF CO2 flux was estimated to be around 35% for AI countries (where the dominating component flux is FL) and 50% for NAI countries (where the dominant flux component is deforestation). Given the incomplete information on the uncertainty of NGHGIs (especially for non-Annex I countries), these values should be considered as rough approximations, which we consider broadly valid also in the context of this study.

In addition, it is worth noting two aspects of the estimation of the annual net C-stock changes and associated uncertainties in forest land, which may represent a bias in the assessed uncertainty.

The first is about the so-called "informal harvesting", i.e. all harvest that is likely not captured by national statistical systems. It includes all harvest that does not meet the criteria set by the country for data collection (e.g. often, wood harvested by small landowners for domestic uses is not captured in statistics), as well as all harvest that is illegally harvested and therefore not reported to the national statistical system. Informal harvest varies largely among countries and may add a bias when the IPCC "gain-loss" approach is used to the estimated annual net CO2 flux from forest. In some cases, this is corrected through proxy data or expert judgement (for instance, Italy reports an annual informal harvest equal to 50% of its total harvest, Italian NIR 2021, annex 14), but in several other cases it may remain uncorrected. In principle, the IPCC "stock-difference" approach is not affected by this problem as it compares the forest biomass stocks between two different inventories.

The second aspect is the ambiguity in the use of the standard error of the mean (SE) vs. the standard deviation of the population (SDp) to calculate the uncertainty of the carbon flux estimates. The SE is appropriate when estimating the annual variation of a variable across the entire population from which the variable has been sampled, e.g. the increment of the entire forest land when the increment value is sourced from national data. In contrast, SDp is appropriate when an average value of the population, e.g. the average per hectare carbon stock is applied to a portion of the population only e.g. the deforested area, or when an IPCC default value is applied to NGHGIs. Although such guidance is provided by IPCC (IPCC, 2019), countries do not always properly use the standard error vs the standard deviation, which leads to underestimating uncertainties when

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the standard error is used instead of the standard deviation or overestimating uncertainties when the standard deviation is used instead of the standard error.

2.5 Comparison with other datasets

We compare our NGHGI DB with other datasets that are conceptually close and also based on country data. First, the forest area is compared with data in the Forest Resources Assessment (FRA) database (FAO, 2020). Second, the carbon fluxes are compared with two other sources:

(i) the LULUCF data directly derived from the UNFCCC GHG data interface (GHGDI, UNFCCC 2021); while the data for AI countries (https://di.unfccc.int/flex_annex1) are the same as the ones used in our study (even if the disaggregation is different), those from NAI countries (https://di.unfccc.int/flex_non_annex1 - which include only NC and BUR submissions) differ. To ensure comparability, for NAI countries we gap-filled the time series of the UNFCCC GHGDI with the same criteria applied in this study (see above). The original (not gap-filled) NC/BUR data from the UNFCCC GHGDI and those collected to build our NGHGI DB are shown in Supplementary Tables 7 and 8, respectively. We note that a compilation of UNFCCC country-reported data (from the UNFCCC GHGDI) is available also in the FAOSTAT web-site, for download and visualisation alongside the FAO emissions estimates (FAO, 2021).

(ii) the LULUCF estimates within the FAOSTAT GHG Database (Tubiello et al. 2022; FAO, 2021), which is used regularly in IPCC Assessment reports (i.e., IPCC, 2019; Tubiello, 2019; Tubiello et al., 2022) and by some countries as an input into data quality analysis in support of their NGHGIs. This paper complements and updates the comparisons of carbon flux estimates between country data to UNFCCC and FAOSTAT for forest land done by Tubiello et al. (2021), which focused on AI and few large NAI countries.

The FAOSTAT GHG Database (Tubiello et al., 2022) includes LULUCF CO_2 fluxes associated with 1) Net Forest Conversion (associated with positive net forest land area loss, tracked separately for FRA forest land sub-categories *naturally regenerating forest* and *planted forest*), which we compare to our Deforestation data; and 2) Forest land, arising from a combination of carbon stock changes per unit of area and net forest area gains between successive FRA periods; fluxes from 3) Drainage and fires in organic soils, which we compare to our ‘’organic soils’’ category. The first two categories are based on country reporting to FAO (via the FRA) of forest land area and above- and below-ground biomass data (FAO, 2020; Tubiello et al. 2021). The latter

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two categories are conversely estimated using geospatial information (Conchedda and Tubiello, 2020; Prosperi et al., 2020; Rossi et al., 2016).

Several aspects need to be considered when comparing our NGHGI DB and FAOSTAT. First, forest land in FAOSTAT is not disaggregated into a managed and unmanaged component, and the values of carbon stocks include all the forest area (Tubiello, et al. 2021), in contrast to the managed forest area included in the country NGHGIs data. This is the main reason why, as explained in Tubiello et al. 2021, FAOSTAT data cannot a priori be assumed to reflect anthropogenic fluxes. In practice, on carbon stocks/ha, the FRA 2020 reports from Canada and Russia explicitly aim to be consistent with UNFCCC reporting and the corresponding managed area, which for these countries is smaller by 0.3 Billion ha than their total forest area. For comparisons, the global managed forest area considered in our NGHGI DB (about 3.5 Billion ha, Figure 1) is within 15% of the total FAO forest land area (4.0 Billion ha).

Second, while the methods used by NGHGIs differ among countries (but all follow the IPCC methodological guidance), FAOSTAT applies the same carbon stock change estimation method to all countries, using the FRA data on biomass stocks and area as inputs. To this regard, our comparison with FAOSTAT data includes an assessment of the completeness/uncertainty of estimates for FL and Deforestation for NAI countries. The approach is illustrated in Supplementary Figure 2. Specifically, the dataset (i.e. NGHGI DB or FAOSTAT) which includes an estimate for FL or Deforestation while the other does not, or the estimate is zero, is considered more complete or less uncertain. Whenever the two datasets appear equally complete or incomplete (for FL and Deforestation), then the completeness of the carbon pools is considered.

3. Results and discussion

3.1 The NGHGI DB: general features

A total of 185 countries out of 195 UNFCCC Parties submitted data on LULUCF CO_2 emissions/removals to UNFCCC, covering 99.9% of the global forest area (Table 3). Contrary to Grassi et al. 2021, where LULUCF data was available only for 106 NAI countries, the NGHGI DB presented here includes data for 142 NAI countries.

Table 3

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Most of the submissions used in the NGHGI DB are recent, i.e. in or after 2019 (80% of countries, corresponding to 86% of absolute CO_2 flux, i.e. the flux calculated by summing the absolute fluxes of the various land categories). Furthermore, approximately 70% of countries (80% of absolute CO_2 flux) used at least in part the 2006 IPCC guidelines to estimate the CO_2 fluxes.

In terms of land use categories, the reporting by AI countries is more complete than NAI countries (Table 4, Supplementary Table 2). The most reported land use is forest land (95% and 89% for AI and NAI countries, respectively). While reporting on Deforestation appears less complete in terms of the number of countries (91% and 55% of AI and NAI countries, respectively), those countries not reporting this category are typically small and with little forest area, i.e., they likely have insignificant or zero emissions from deforestation. Overall, it can be assumed that the vast majority of countries where significant fluxes from deforestation are likely to occur do report some data. This however, does not necessarily imply that the reported data is accurate. Emissions from organic soils are assumed to be reported (even if sometimes not explicitly separated from mineral soil) by all AI countries where a relevant area of organic soil occurs on managed land. By contrast, only few NAI countries report emissions from the drainage in organic soils and Indonesia is the only one to report the emissions from peat fires. Nonetheless, significant improvements are expected in the coming years as a result of several international initiatives on peatlands.

Table 4.

3.2 Forest Land area

Here we compare the information on forest area compiled in the NGHGI DB with the data reported by countries to FAO via the FRA (FAO, 2020) as disseminated in FAOSTAT.

Overall, 150 countries reported information on forest land area under the UNFCCC. Conversely, 189 countries reported data to FAO on forest land area, including in most cases its disaggregation into FRA components of *naturally regenerating forest* (a category that includes both primary and naturally regrowing, or secondary, forest) and *planted forest* (Table 5 and Supplementary Table. 3). The difference in the number of country reporting between UNFCCC and FAO is due to a group of NAI countries, corresponding in FRA to a total

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area of 46 Mha (about 1% of the global forest land area in 2015). The FAO data for these countries were used in the NGHGI DB to gap-fill the missing UNFCCC data (see Supplementary Table 3).

Similarly, the area of unmanaged forest could be derived only from 9 NGHGIs (Tab. 5), compared to 91 countries that reported primary forest to FAO. While all AI countries explicitly report both managed and unmanaged forest area to UNFCCC (with unmanaged area being often zero), the vast majority of NAI countries do not explicitly make this separation in their NGHGIs. In the absence of additional information (e.g. see the information collected and the assumptions made for Colombia, Ecuador and Peru, Supplementary Table 1), and following the example of most AI countries, we assume that forest land area reported to UNFCCC is managed. The significance of this assumption is that, according to the IPCC Guidelines (IPCC 2006), all emissions and removals from managed lands are considered 'anthropogenic', while those from unmanaged lands do not need to be reported. The lack of specific information on managed land area from many NAI countries (particularly on managed forests) represents an important gap of information to assess the extent of anthropogenic CO_2 fluxes.

Table 5.

Figure 1 compares the distribution of managed and unmanaged forest in our NGHGI DB with that of secondary forest/ plantation and primary forest from FAO, at global levels and for five macro regions (AI countries are in panels b and c; NAI countries are in panels d-f). While there is a general convergence between the two datasets on the total forest area, some differences emerge when comparing managed vs. secondary/plantation and unmanaged vs. primary. The main reason is that managed forest and secondary/plantations (or unmanaged and primary) are not necessarily synonyms. In fact, managed forest under UNFCCC includes areas that fulfil social, ecological and economic functions (IPCC 2006) and that may therefore apply to both primary and secondary forest land, depending on country-specific definitions and situation. For example, based on the detailed information provided in FRA country reports that accompany that data submitted to FAO, many AI countries (including Canada, Russia and USA) consider relatively large areas of primary forest as managed. At the same time, we note nonetheless that "forest" area is generally reported by countries to both UNFCCC and FAO using the same underlying bio-physical characteristics, specifically, minimum area, minimum tree height at maturity and minimum crown closure.

Figure 1

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3.3 CO_2 fluxes: the NGHGI DB

The NGHGI DB indicates a net mean global LULUCF sink of -1.6 Gt CO_2/yr over the period 2000-2020 (Fig. 2a). The LULUCF sink is largely determined by a forest land sink (-6.4 Gt CO_2/yr) and a deforestation source (+4.4 Gt CO_2/yr), as well as by smaller land fluxes that nearly cancel each other out, i.e. including organic soils (+0.9 Gt CO_2/yr) and 'Other' (-0.6 Gt CO_2/yr). Country-level data are included in Supplementary Tables 4 (LULUCF net CO_2 flux, not gap-filled), 5 (LULUCF flux gap-filled), 6 (CO_2 flux by land use and land use-change category, gap-filled) and 7-10 (more detailed information from NAI country submissions).

A slight trend of decreasing CO_2 emissions from deforestation and increasing CO_2 removals from forests is present for the NAI country group (Fig. 2b). By contrast, the AI country group shows no clear trend.

Figure 2.

Figure 3 shows the LULUCF CO_2 fluxes in the period 2000-2020 for the largest Annex I and non-Annex I countries, suggesting that the level and trend of global carbon fluxes is largely determined by relatively few large countries.

Figure 3.

We further tested the dependence of NGHGI DB on the choice of gap-filling, noting that only 54% of the NGHGI DB data are directly derived from country reports. To this end, we compared our results with two equally reasonable alternatives for gap-filling on the resulting level and trends of carbon fluxes. The first alternative, i.e., a simple average of the original non-gap-filled data in each country for 2000-2020, results in a global LULUCF net sink (-1.58 Gt CO_2/yr) very close to the one obtained with our gap-filling procedure (-1.64 Gt CO_2/yr); qualitatively identical results are obtained when the analysis is done at the level of specific land categories (forest land, deforestation). The second alternative, i.e. no linear interpolation between two data points (see Methods, produced a global net sink of -1.69 Gt CO_2/yr for 2000-2020 and a trend which is very similar to the one of our NGHGI DB (Supplementary Fig. 3). This indicates that the global levels and trends that are highlighted by the NGHGI DB data are robust across a range of credible gap-filling procedures.

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Furthermore, the analysis of UNFCCC country data with information on forest fluxes (all AI and 20 NAI countries) indicates that the majority of the reported sink in forest land (FL) is unevenly distributed across the two sub-categories forest land remaining forest land (FL-FL) and land converted to forest land (L-FL). Specifically, countries report that the vast majority of their forest sink is in FL-FL (87% globally, 88% in AI countries and 85% in NAI countries), while only 13% is in L-FL. This is consistent with the small carbon sequestration role expected in younger forests typical of the L-FL category which, though sequestering large amounts of carbon per unit area as they grow, occupy a small area compared to older forests in FL-FL. For example, for AI countries, the area of L-FL is only 8% of total forest area and 12% of the total forest sink.

Here we use uncertainty values for the net LULUCF flux from Grassi et al (2021) - i.e. around 35% for AI countries and 50% for NAI countries. It is important to recognize that additional uncertainties, not addressed by statistical means, may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models (IPCC 2006). Furthermore, it should be noted that - in the context of country GHG reporting to UNFCCC - the uncertainty analysis should be seen, first and foremost, as a means to help prioritise national efforts to reduce the uncertainty of inventories in the future, and guide decisions on methodological choice (IPCC 2006). To this regard, in the context of review / technical assessment processes under the UNFCCC, a greater focus on the informal harvesting and the correct calculation of uncertainties (see Methods) would help countries in improving their national estimates and the assessment of the associated uncertainty.

3.4 CO_2 fluxes: comparing the NGHGI DB and the UNFCCC GHG Data Interface (UNFCCC GHGDI)

For 2000-2020, the UNFCCC GHGDI (gap-filled for NAI countries) includes a much greater net LULUCF sink globally (-5.4 Gt CO_2/yr) than reported in our NGHGI DB (-1.6 Gt CO_2/yr). This is entirely due to results in NAI countries, for which the UNFCCC GHGDI gives a global mean net sink of -3.4 Gt CO_2/yr and the NGHGI DB conversely a source of 0.4 Gt CO_2/yr. Note that, when the original (not gap-filled) data from NAI countries are compared instead the gap-filled ones - i.e. taking the average for 2000-2020 of the available data for each country - the results do not significantly change (i.e. -3.28 Gt CO_2/yr in UNFCCC GHGDI and +0.43 Gt CO_2/y in our NGHGI DB). The countries with the biggest difference in carbon flux between our NGHGI DB and the UNFCCC GHGDI are illustrated in Table 6.

We identify two reasons for the large difference (3.8 Gt CO_2/yr) between the two sources.

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First, the UNFCCC GHGDI includes only NC/BUR in the format of, and sometimes methodologically consistent with, the Revised 1996 IPCC Guidelines (IPCC 1996), because the inclusion of GHG data reported in the format of the 2006 IPCC Guidelines has not yet been agreed by Parties. This explains a difference of 0.7 Gt CO_2/yr due to the inclusion, within our NGHGI DB, of data according to both the 1996 and 2006 IPCC formats.

Second, our NGHGI DB includes country submissions (i.e., REDD+ and NDCs, if clearly more recent than NCs/BURs, see Methods) which are not included in the UNFCCC GHGDI. This explains a further 3.1 Gt CO_2/yr difference. For example, for the Central African Republic, the UNFCCC GHGDI includes an exceptionally high net sink from the 2015 NC (-1.7 Gt CO_2/yr), while our NGHGI DB includes a net LULUCF sink of -0.2 Gt CO_2/yr reported in the more recent NDC (2016).

Due to the two reasons above, our NGHGI DB is more complete for NAI countries, containing more than twice the number of yearly values of carbon fluxes than the UNFCCC GHGDI.

For some countries, this second reason may include difficulties in identifying what area and what anthropogenic LULUCF fluxes to include (especially for the forest sink), possibly resulting in different choices made for different types of submissions. These difficulties may reflect the different IPCC methodological guidance used. The 1996 Revised IPCC Guidelines (IPCC 1996) - still used by several NAI countries, especially small ones - do not include a definition on managed land, which is a concept introduced by the IPCC Good Practice Guidance on LULUCF (IPCC 2003) and retained by the 2006 IPCC Guidelines later. According to IPCC (2003), emissions and removals from managed land are recommended as a proxy for anthropogenic emissions and removal. Specifically, forest management is defined as "*the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest*" but also suggests that "*…natural, undisturbed forests should not be considered either an anthropogenic source or sink and are excluded from national inventory estimation*." The 2006 IPCC Guidelines (IPCC 2006) - further confirmed in the 2019 IPCC Refinement (IPCC 2019) - suggest that national definitions of managed forest should cover all forests subject to human intervention, including as management practices protecting forests and abandonment of managed land. This may raise challenges on the exact coverage of managed forests to be included: for example, forests inside a national park can fulfil a relevant ecological function, and be actively protected while being natural and undisturbed.

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Related to the above, many REDD+ and NDC submissions tend to focus more on emissions than on removals, compared to NCs/BURs. In the first case, it is explainable by the aim of the REDD+ framework. For NDCs, the greater focus on emissions compared to NC/BUR could be potentially explained by the difference existing for the LULUCF sector between 'reporting' of GHG fluxes - which in principle should include all the fluxes in managed lands - and 'accounting', i.e. the use of reported information to meet specific mitigation targets. For the purpose of accounting, the reported GHG fluxes may be potentially filtered through a more restrictive interpretation of 'anthropogenic' flux, with the aim to better reflect the impact of mitigation actions (see Supplementary Information in Grassi et al. 2021). In this study we focus on the reporting, i.e. on the carbon fluxes that the countries estimate for the historical period in their managed land and report to UNFCCC. Even if we found no evidence suggesting that the NDCs included in our dataset report a smaller sink than in the NC/BUR because the former apply a more restrictive interpretation of 'anthropogenic' flux, this possibility cannot be ruled out.

Overall, the above suggests that a more explicit identification by NAI countries of what they consider to be 'anthropogenic' sink would be important to achieve more clarity on global LULUCF fluxes.

Table 6.

Understanding the difference between our NGHGI DB and the UNFCCC GHGDI is important to interpret other analyses. For example, The Washington Post (2021) estimated a global net LULUCF sink of -3.6 Gt CO_2/yr in 2019, while for the same year our NGHGI DB estimates -1.9 Gt CO_2/yr (Supplementary Table 5). The difference (1.7 Gt CO_2/yr) is mostly due to the fact that the Washington Post, apart from excluding the value for the Central African Republic, is based on the UNFCCC GHGDI, which appears to be less comprehensive and updated than our NGHGI DB (see above).

3.5 CO_2 fluxes: comparing the NGHGI DB to FAOSTAT emissions estimates

While the trends of the LULUCF component categories are consistent across the two datasets (Fig. 4), there is a large difference in total net LULUCF fluxes, amounting to 2.7 Gt CO_2/yr (-1.6 vs. +1.1 for NGHGI-DB and FAOSTAT, respectively) averaged over the 2000-2020 period (Fig. 4a, 5a). This difference is mainly driven by a much larger estimated net forest land sink in the NGHGI DB (-6.4 Gt CO_2/yr) compared to FAOSTAT (-

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3.2 Gt CO_2/yr) (Fig. 5b). Conversely, the two datasets are closer on deforestation, albeit the NGHGI DB has consistently higher emissions than FAOSTAT for NAI countries (Fig. 5c). For organic soils, there is notable agreement both on estimated absolute values as well as in the inter-annual variations of emissions for both AI and NAI countries (Fig. 5d). This is remarkable, considering that the NGHGI DB is not very much gap-filled for this category (considering that the largest NAI emitters, and particularly Indonesia, report these emissions estimates to UNFCCC), and that the FAOSTAT estimates are based on FAO's own geospatial analysis (Conchedda and Tubiello, 2020).

Figure 4.

Figure 5.

Overall, the differences may be explained by a combination of factors, which we discuss below separately for AI and NAI countries, and for each category.

In AI countries, the NGHGIs are typically more complete in terms of land categories and carbon pools compared to FAOSTAT. In particular, for FL, a comparison of AI countries' data from NGHGIs and FAOSTAT has already been done by Tubiello et al. (2021). The differences that emerge here, between the NGHGI DB and FAOSTAT, can be mostly explained by estimates for pools other than living biomass, including HWP, included in the NGHGI DB but not in FAOSTAT. This explains a difference of about 0.2 Gt CO_2/yr just for the USA, and a similar amount for other developed countries together (Fig. 6a). For the category 'other' - i.e. non-forest land uses, excluding organic soils, which are not included in FAOSTAT - our NGHGI DB reports a net sink of -0.23 Gt CO_2/yr. At the same time, for organic soils, NGHGI DB and FAOSTAT report similar numbers at global level (Fig. 5d), with a good agreement also for AI and NAI countries.

In NAI countries, for FL, we find a large difference in the carbon flux between our NGHGI DB and FAOSTAT data, resulting in a -2.7 Gt CO_2/yr greater sink in NGHG DB for 2000-2020 (Fig. 5b). This difference, which alone explains most of the gap between the two datasets, is largely linked to two factors.

On the one hand, the NGHGI DB contains a forest sink from five NGHGIs which we consider implausible (see Methods), possibly due to the inaccurate implementation of the IPCC methodology (the UNFCCC review of some of these reports already signalled this). Collectively, these countries report a net LULUCF flux of -0.9 Gt CO_2/yr over the period 2000-2020, with no clear trend. These five countries are located in Africa (Central African Republic, Mali, Namibia) and South-East Asia (Malaysia, Philippines).

The second factor relates to the large underlying uncertainty in measurements of carbon stock changes over time. The capacity of many NAI countries is insufficient to ensure provision of consecutive and consistent forest inventories. For this reason, many NAI countries report to FAO via the FRA, likely for lack of better information, a constant value of forest carbon stock density (carbon stock/ha) over the period analysed here (2000-2020). In such cases, the estimated carbon stock changes in FAOSTAT necessarily represent net fluxes on either L-FL (positive net forest land area change) or FL-L (negative net forest land area change), while the estimated fluxes on FL-FL are zero. Conversely, when the same NAI countries report to UNFCCC, they may choose to apply the default IPCC gain-loss approach to compute and report non-zero carbon fluxes over FL-FL. This is relevant, because FL-FL is typically where most of the FL carbon flux occurs, considering the much larger underlying areas of FL-FL compared to L-FL in most countries. More specifically, the carbon stock change approach implemented in FAOSTAT results in a non-zero carbon flux for FL-FL in only 63 NAI countries, compared to 136 in countries NGHGIs (Table 7). The remaining 89 NAI countries have a total forest land area of 905 Mha (i.e. 41% of forest area in NAI countries, mostly in Africa and South America, Figure 6a), where the underlying FRA data on carbon stock density is lacking or constant over the entire period 2000-2020. Conversely, only 16 NAI countries in our NGHGI DB report no carbon fluxes on FL-FL (Table 7), corresponding to 272 Mha of forest (mostly in Africa, Figure 6a). The underlying reasons for these differences are further explained in Box 1, and can be summarized by the different scopes of the two country datasets: while FAO reporting via the FRA focuses on measures of area and biomass (without a focus on climate change relevant fluxes), UNFCCC explicitly asks countries to report a value of *carbon flux*, providing default methods and factors that can be used despite the underlying paucity of national data.

We note that, when countries do report a non-zero value of FL-FL, these values are most often a sink in both NGHGIs and FAOSTAT, although with features that would merit a more nuanced analysis. Based on this, we estimate a hypothetical sink that could have occurred on those FL areas with no or zero value of carbon flux. To this aim, we used the mean net annual area-specific sink for NAI countries from our NGHGI DB (of -1.9 tCO_2/ha*yr, excluding the countries with implausible FL sinks) and FAOSTAT (of -1.1 tCO_2/ha*yr, excluding those countries reporting a constant carbon stock/ha under FRA). Acknowledging the uncertainty of this exercise, this approach would yield a greater global forest sink, by about -1.0 Gt CO_2/yr in FAOSTAT and of -0.5 Gt CO_2/yr in our NGHGI DB.

Table 7.

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Figure 6.

BOX 1. The challenge of estimating the biomass carbon fluxes in forest land remaining forest land (FL-FL)

While carbon fluxes on forest land remaining forest land are a critical component of the land carbon budget, they are typically one of the most difficult to estimate, because they result from small area-specific net carbon stock changes, which are difficult to detect over short time intervals and over large areas.

To estimate this carbon flux in the biomass C pool, two approaches are available from the IPCC: the "gain-loss" approach and the "stock difference" approach.

The stock difference approach estimates the FL-FL carbon flux based on the difference between two carbon stocks over time. This approach always requires country-specific values of stock, e.g. from at least two subsequent, methodologically-consistent, national forest inventories based on representative sampling. The challenge is availability of good data to use as inputs into these computations. Specifically, very few NAI countries have conducted two or more methodologically-consistent national forest inventories, which would be necessary to apply the stock difference approach. For example, of the 56 REDD+ reporting countries, only very few use subsequent forest inventories to estimate the stock-difference in FL-FL.

The gain-loss approach is the IPCC default method, since it associates each C stock change to its driver and therefore provides needed policy-relevant information; while the stock-difference approach is more straightforward in terms of measurement requirements, it provides no information on the drivers that determined the net C stock change. The gain-loss approach estimates the flux through net forest growth (i.e. considering mortality), minus losses from harvest and natural disturbances using country-specific or IPCC default values for net growth, and country statistics for losses from harvest and natural disturbances. This approach can however have large uncertainty in the estimated net C stock change, especially where the losses are under-estimated, which could easily happen where not all harvest is not recorded in country statistics. Furthermore, the default IPCC net biomass growth factors (IPCC 2019) come with very large uncertainties. For example, in most regions of the tropical domain, the standard deviations are >100% for primary forest and >70% for secondary forest. Gatti et al (2021) and Hubau (2020) indicate that net biomass growth factors likely declined in the last decades in some tropical forests (Amazonia); this would imply that, when applying constant increment rates across decades, as e.g. per IPCC default factors, net removals from FL-FL could be

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overestimated if these factors were estimated decades back. On the other hand, Cook Patton et al. 2020 suggests that default rates from IPCC underestimate aboveground carbon accumulation rates by 32 per cent on average, especially in tropical regions.

FAOSTAT calculates emissions/removals based on data from the country reports to FRA. Under FRA, countries are expected to provide a time series of values of forest area, biomass, carbon stock and carbon stocks/ha, but are not asked to provide a carbon flux or carbon stock change. The absence of country specific values of forest carbon stocks changes from successive national forest inventories indeed is the most likely reason explaining why so many NAI countries report constant time series of carbon stock/ha, whereas some changes, either positive or negative, are to be expected.

By contrast, the UNFCCC specifically requests countries to provide a net value of carbon flux in their NGHGIs. In the absence of successive national forest inventories to apply the stock difference approach, the gain-loss approach may be applied. In this case, when the required country-specific values are not available (e.g., forest growth), the gain-loss approach may use values sourced from IPCC defaults complemented by country data on losses (harvest, and other disturbances' mortality).

In summary, the differences above reflect mainly the different scopes of the country reporting to FRA, which focuses on area and biomass variables, and to UNFCCC, which explicitly focuses on carbon fluxes. It also underscores the challenges to estimate the fluxes in FL-FL in absence of accurate country data, like in many NAI countries. In the frequent case where multiple national forest inventories are not available or not comparable, a single value of carbon stock might be considered sufficient to describe the state of the forest under FRA - but not under the UNFCCC, where the focus is in fact carbon fluxes. In the latter case, correspondents are guided, even in the absence of national data, to use the IPCC gain-loss approach.

- **End of the box –**

For NAI countries, the emissions from deforestation are estimated in 141 countries by FAOSTAT (*net forest conversion)* compared to 124 countries in our NGHGI DB. Since FAOSTAT computes the emissions for net forest land area loss, data would roughly correspond to those countries using the so-called "IPCC approach 1" to land representation (Tubiello et al., 2021). By contrast, NGHGI reporting is usually based on a more detailed tracking of the conversions between land uses and the associated gross fluxes. This difference may partly explain why our NGHGI DB estimates somewhat larger emissions from deforestation for NAI countries than

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in FAOSTAT (Fig. 6b). Furthermore, in FAOSTAT, the use of a single average forest carbon stock density may lead to underestimation of emissions (Tubiello et al. 2021). Other possible confounding factors in comparing deforestation estimates across datasets may be different reporting by NGHGIs of shifting agriculture and forest degradation processes: depending on the country and the report, the fluxes from these processes may be reported either under FL or as additional deforestation.

Although the rates of emissions from deforestation differ in the two databases, the trends look similar, both for the area and for the emissions. Comparing 2015-2020 against 2000-2005, FRA reports a 33% reduction in deforestation area, and our NGHGI DB and FAOSTAT estimate a 18% and 20% reduction of emissions from net forest loss, respectively. The trends for our NGHGI DB and FAOSTAT look rather similar also for the macro regions analysed here, with emissions increasing in Asia and Africa while decreasing in South America (Supplementary Fig. 4). It should be noted, however, that both datasets may fail to capture any recent increase in deforestation, such as those detected in the last years in Brazil (e.g., Silva Junior et al. 2020).

Donegan et al. (forthcoming) found the trends in FAO-FRA to be in overall agreement with the satellite-based assessment in the JRC's tropical moist forest dataset (Vancutsem et al. 2020). A similar trend emerges also in the Global Carbon Budget 2021 (Friedlingstein et al. 2021), based on bookkeeping models. However, this in contrast with analyses based on the Global Forest Change product (GFC, Hansen et al. 2013), which indicates an increasing tree cover loss. Recent evidence indicates that the GFC's trend seems partly or largely explained by an increased capacity of the product to detect changes after 2015 (Palahi et al. 2021, Ceccherini et al. 2021), but other studies (Feng et al. 2022) confirm the GFC's trend also after an effort is made to address its temporal inconsistencies. While acknowledging that tree cover loss does not necessarily imply a land use change, these contradictory trends are striking. Given the renewed political interest in reducing deforestation emerged at the UNFCCC's conference in Glasgow in 2021 (COP 26), reconciling the differences above is a priority for the scientific community.

In NAI countries, the fluxes in the category "other" in our NGHGI DB, which are not included in FAOSTAT, represent a net sink of -0.35 Gt CO_2/yr, mostly from cropland and grasslands in China and India. For organic soils, FAOSTAT's estimates include several NAI countries that do not report such emissions in the NGHGIs; this may explain 0.06 Gt CO_2/yr difference between our NGHGI DB and FAOSTAT.

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To gain more confidence in our analysis for NAI countries, we made an additional assessment of the completeness/uncertainty of reporting for FL and Deforestation in our NGHGI DB and FAOSTAT (including the country reports to FRA). We took into account the cases of implausible forest sink in few NGHGIs, whenever the carbon flux for FL-FL is zero in FAOSTAT, and the carbon pools considered in the two sources (see methods). This assessment should be considered as broadly indicative of the level of process coverage of the two datasets, with the aim to help potential users.

Results show (Table 8) that in 73 cases, the NGHGI DB appears more complete/less uncertain on carbon fluxes, especially in those cases where FAOSTAT estimates zero carbon fluxes on FL-FL (that is, in the assumption that an estimated default carbon flux represents more information than a single value of carbon stock reported over time), and more complete on the carbon pools included. In 27 cases, FAOSTAT includes a more plausible forest sink or a more complete/less uncertain reporting than in our NGHGI DB, especially for deforestation in small countries. For the remaining 52 countries, both databases appear incomplete or the outcome of the assessment is uncertain.

Table 8.

Figure 7 summarizes the outcome of our analysis, for both AI and NAI countries, to help understanding the reasons for the large differences between our NGHGI DB and the UNFCCC GHGDI (+3.8 Gt CO_2/yr on average for 2000-2020), and between the NGHGI DB and FAOSTAT (-2.7 Gt CO_2/yr).

In the first case, the difference is due to the fact that the NGHGI DB is more updated and comprehensive than UNFCCC GHGDI for NAI countries, i.e. it includes NC/BUR which use the 2006 IPCC categories, and also REDD+ or NDC submissions if more recent than NC/BUR.

When comparing the NGHGI DB and FAOSTAT, about 59% of the total difference (1.6 Gt CO_2/yr, Figure 7) may be explained by a more complete/less uncertain reporting by the underlying NGHGIs included in our dataset, in both AI and NAI countries; in terms of land categories (especially non-forest land uses in AI countries, and FL-FL in NAI countries) and of non-biomass carbon pools (especially in FL). Another 15% (0.4 Gt CO_2/yr) can be explained by more plausible sinks or more complete/less uncertain reporting in FAOSTAT than in the NGHGI DB for NAI countries, including on organic soils. For the rest 26% of the gap (0.7 Gt CO_2/yr), it is difficult to identify a clear reason, and often both datasets appear rather poor.

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Figure 7.

4. Conclusions

The NGHGI DB presented in this study provides access to an up-to-date, comprehensive and gap-filled source of information on LULUCF carbon fluxes at country level, based on official country data submitted to the UNFCCC (both Annex I and non-Annex I countries). The database is disaggregated into the following components: i) forest land (of which we track separately forest land remaining forest land, FL-FL); ii) deforestation; iii) organic soils; and iv) other land fluxes (including non-forest land uses). The NGHGI DB results in a net global sink of -1.6 Gt CO_2/yr, averaged over the period 2000-2020. This is due to a balance between a large forest land sink (-6.4 Gt CO_2/yr, mostly on FL-FL), and a large land source from deforestation (+4.4 Gt CO_2/yr). Other relevant fluxes include those from drainage and burning of organic soils (+0.9 Gt CO_2/yr), and from other land uses (-0.6 Gt CO_2/yr).

With reference to the range of UNFCCC data that are used as input into the NGHGI DB, Annex I countries explicitly identify area of managed land (for which anthropogenic GHG fluxes are to be reported) and unmanaged land. Conversely, only few non-Annex I make this distinction explicit in their reported data. In the absence of more specific information, and in line with the basic scope of UNFCCC reporting, we assume that all fluxes reported are anthropogenic, and that the corresponding land area is managed. For the future, a more explicit identification by non-Annex I countries of what is considered managed area and anthropogenic GHG flux would be important to achieve more clarity on the global LULUCF fluxes.

Our NGHGI database is then compared with two LULUCF datasets that are conceptually close and also based on country data: the UNFCCC GHG data interface, which reports a global net sink of -5.4 Gt CO_2/yr, and the LULUCF component of the FAOSTAT emissions database, which results in a global net source of +1.1 Gt CO_2/yr averaged over the same 2000-2020 period. In the first case, the difference is due to the fact that our NGHGI DB includes more recent data from NAI countries than the UNFCCC GHGDI, including from REDD+ submissions (which go through a detailed technical assessment) and NDC submissions.

In the second case, the NGHGI DB reports larger deforestation fluxes than FAOSTAT (+25% difference, within the underlying uncertainty in both products), possibly due to the fact that FAOSTAT's estimates are

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typically based on net forest area change, rather than gross deforestation as usually done by NGHGIs, and use a single country value of forest carbon stock density for both primary/secondary and planted forest. On the other hand, some NGHGIs may include shifting agriculture in their deforestation emissions.

Importantly, the NGHGI DB results in sink on forest land (-6.4 Gt CO_2/yr) which is much larger than FAOSTAT (-3.2 Gt CO_2/yr on average over 2000-2020), especially in non-Annex I countries. While it can be assumed that no or few countries with major deforestation rates are missing from both datasets, significant data gaps exist in non-Annex I countries with respect to fluxes on forest land. In particular, the carbon flux on FL-FL (where the majority of the forest carbon flux typically occurs) is not estimated or estimated as null over large areas, i.e. 272 Mha in the NGHG DB and 905 Mha in FAOSTAT. Whereas the use of IPCC gain-loss method allows most NAI NGHGIs to estimate a forest carbon flux, the underlying data are uncertain (e.g., on forest growth) or may be biased (e.g., harvest may be underestimated). By contrast, when country-level data on carbon stock changes are lacking in the FRA reports (especially in Africa), FAOSTAT provides no or null estimates for the forest carbon flux. These gaps imply a large uncertainty in the FL fluxes, likely proportional to the areas above for the NGHGI DB and FAOSTAT, which undermines further progress in assessing the net LULUCF fluxes and mitigation efforts. In addition, the net LULUCF flux in five NGHGIs - collectively amounting to -0.9 Gt CO_2/yr - appears implausibly high.

Overall, most of the difference between our NGHGI DB and FAOSTAT can be explained by more complete/less uncertain reporting of carbon fluxes by the NGHGIs included in our database (Figure 7), especially on FL-FL of non-Annex I countries, on non-biomass carbon pools and non-forest land uses. This mainly reflects the different scopes of the country reporting to FRA, which focuses on forest area and biomass variables (upon which FAOSTAT's estimates for FL are based), and to UNFCCC, which explicitly focuses on LULUCF carbon fluxes. Indeed, compared to the data included in our NGHGI DB, FAO provides more complete information on forest areas (including primary and secondary forests and plantations) and on carbon stocks, which are important parameters for modelling purposes. Both the NGHGI DB and FAO – bearing in mind the respective strengths and weaknesses – offer a fundamental, yet incomplete, source of information on carbon-related variables, representing a key source of information for both scientific and policy communities, including under the Global Stocktake.

For the future, the quality of NGHGIs is expected to improve following the full implementation of Enhanced Transparency Framework under the Paris Agreement. Based on our findings, we suggest that priority areas of

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improvement for non-Annex I countries - where UNFCCC reviewers and capacity building support should also focus on - include the explicit identification of managed vs unmanaged forest areas (which is crucial to understand if the reported flux is considered anthropogenic), the plausibility of the forest sink and the completeness of reporting. For FRA data, where relevant improvements have already occurred (Nesha et al. 2021), future efforts may focus on increasing consistency with NGHGIs. Meanwhile, in the absence of appropriate data sources per country, it should be evaluated whether carbon fluxes can be estimated from reported carbon stocks over time.

In summary, although the quality and quantity of LULUCF data in NGHGIs improved considerably in recent years, our database highlights that some important gaps still remain, especially in non-Annex I countries. Addressing these gaps should be seen as a priority to increase confidence in land-use mitigation under the Paris Agreement and facilitate comparison with independent scientific estimates. With these limits in mind, the NGHGI DB presented is the most up-to-date and complete source of LULUCF CO_2 fluxes based on country submissions to UNFCCC.

Data availability

Data from this study are openly available via the Zenodo portal (Grassi et al. 2022), https://doi.org/10.5281/zenodo.6390739

Author contribution

G.G. led the study design with the help of S.F. and F.N.T., performed the analysis and wrote the first draft. S.F., R.A.V., A.K., S.R. and J.M. contributed to the collection of the data from country reports. G.C., M.S., and Z.S contributed to the analysis. All authors contributed to the drafting.

Competing interests

The authors declare that they have no conflicts of interest.

Disclaimer

The views expressed are purely those of the writers and may not under any circumstances be regarded as stating an official position of the European Commission, FAO or any other institution.

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TABLES

Table 1. Overview of the main characteristics of the sources of data used in this study.

	DATASET USED		**CO_2 flux**	**Forest area**	**Latest update**	**Time series**	**Comment by the authors**
Annex I countries (AI)	**GHGI**	GHG Inventories (GHGI) https://unfccc.int/ghg-inventories-annex-i-parties/2021	All land uses	yes	2021	1990-2019	Rather complete and generally reliable source. Based on the 2006 IPCC Guidelines (IPCC 2006). Reviewed annually by UNFCCC experts. Standardised tables.
Non-Annex I countries (NAI)	**NC or BUR**	National Communications (NC) or Biennial Update Reports (BUR) https://unfccc.int/non-annex-I-NCs, https://unfccc.int/BURs	In principle, all land uses. In practice, mostly forest land (FL) and Deforestation (DEF)	Yes. Here we used FRA 2020 data to gap fill where this information is missing	After 2018 for most countries	Varies from country to country	The quantity and quality of information varies considerably among countries, but is improving with time. Technically assessed by UNFCCC experts (not an in-depth review). Typically, not standardised tables. Numbers are taken from available tables or, in the absence of these, are approximately derived from the figures reported. The 1996 or 2006 IPCC Guidelines are used.
	REDD+	Submissions to 'Reducing Emissions from Deforestation and forest Degradation' (REDD+) https://redd.unfccc.int/submissions.html?mode=browse-by-country	The following activities may be reported: DEF: reducing emissions from deforestation. DEG: reducing emissions from forest degradation. CCS: conservation of forest-carbon stocks. ECS: enhancement of forest-carbon stock. SFM: sustainable management of forests. DEF and DEG are the most reported activities	yes	After 2018 for most countries that submitted under REDD+	Varies from country to country	The quantity and quality of information on forest and deforestation is typically greater than that of NC/BUR, but often estimates do not cover the entire national forest land area and all associated CO_2 fluxes. Estimates tend to be activity-based and often do not cover the forest land sink. Technically assessed by UNFCCC experts (in-depth review). Non-standardized tables. Generally, this source is used in our NGHGI DB if estimates are spatially complete (full national coverage) and if more than one activity is included (e.g. Deforestation and forest Degradation). Typically, the 2006 IPCC Guidelines are used
	NDC	Nationally Determined Contributions (NDC) https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx	Mostly FL and DEF.	yes, FRA 2020 used to gap fill	Mostly from 2021	Varies from country to country	The quantity and quality of information varies considerably among countries; typically, much less information is provided than NC/BUR or REDD+, and the methodological basis is not always clear. Not assessed by UNFCCC experts, but when nothing better was available it is used here because it is a highly relevant information under the Paris Agreement. Non-standardized tables. Numbers are taken from available tables or, in the absence of these, are approximately derived from the figures.

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Table 2. Mapping of original categories in the country report (typically those of the IPCC methodology) to the categories used in this study (Forest land, Deforestation, Organic soils, Other).

Original categories in the country reports		**Categories in this study**
IPCC 2006 categories	A. Forest land	FOREST LAND
	1. Forest land remaining forest land	FOREST LAND
	2. Land converted to forest land	FOREST LAND
	B. Cropland	If this category has no further disaggregation (e.g. in many NAI countries), it is assigned to "OTHER" or to "DEFORESTATION" depending on the additional information available in the country report.
	1. Cropland remaining cropland	OTHER
	2. Land converted to cropland	If this category has no further disaggregation, it is assigned to "OTHER", or (more often) to "DEFORESTATION", depending on the additional information available in the country report. If further disaggregation is available (e.g. all AI countries), the mapping follows this more detailed information (e.g.,"forest converted to cropland" becomes "DEFORESTATION", while "grassland converted to cropland" becomes "CROPLAND")
	C. Grassland	As above for cropland
	1. Grassland remaining grassland	OTHER
	2. Land converted to grassland	As above for land converted to cropland
	D. Wetlands	As above for cropland
	1. Wetlands remaining wetlands	OTHER
	2. Land converted to wetlands	As above for land converted to cropland
	E. Settlements	As above for cropland
	1. Settlements remaining settlements	OTHER
	2. Land converted to settlements	As above for land converted to cropland
	F. Other land	As above for cropland
	1. Other land remaining other land	Not applicable
	2. Land converted to other land	As above for land converted to cropland
	G. Harvested wood products	FOREST LAND
IPCC 1996 categories	Changes in forest and other woody biomass stocks	FOREST LAND
	Abandonment of managed lands	FOREST LAND
	Forest and grassland conversion	If this category has no further disaggregation, it is assigned to "OTHER", or more often to "DEFORESTATION" (e.g. if it is an emission), depending on the additional information available in the country report. If further disaggregation is available, the mapping follows this more detailed information (e.g., "forest converted to pasture" becomes "DEFORESTATION", while "pasture converted to cropland" becomes "OTHER")
	Managed soil	OTHER
	Biomass burning	FOREST LAND
Mixed categories	"AFOLU CO_2 removals" or "LULUCF CO_2 removals"	FOREST LAND (this is supported by the fact that, when a more disaggregated reporting is available, the vast majority of the CO_2 removals occur in forest land)

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	"AFOLU CO2 emissions" or "LULUCF CO2 emissions"	DEFORESTATION (this is supported by the fact that, when a more disaggregated reporting is available, the vast majority of the CO_2 emissions are associated to deforestation)
	"AFOLU net CO_2 flux" or "LULUCF net CO_2 flux"	FOREST LAND where it is a net removal, DEFORESTATION where it is a net emission (this is supported by the fact that, when a more disaggregated reporting is available, the vast majority of the CO_2 removals occur in forest land and the vast majority of the CO_2 emissions are associated with deforestation)
Emissions from managed ORGANIC SOILS for AI countries are taken from the detailed reporting in CRF tables, and are subtracted from the respective categories (forest land, deforestation, other). For NAI countries, only Indonesia reports emissions from peat decomposition and peat fires, which we both assigned to ORGANIC SOILS.		

Table 3. Statistics on the sources used in this study for Annex I (AI) and Non-Annex I (NAI) countries.

Source used		**N. of countries**	**Forest area***		**Absolute** CO_2 flux (%)**
			Mha	**%**	
AI countries	**GHGI**	43	1943	45%	25%
NAI countries	**NC/BUR**	108	1874	44%	59%
	REDD+	20	176	4%	5%
	NDC	14	292	7%	12%
	No LULUCF data	10	4	0.1%	0%
Total		195	4288		

* The forest area includes 46 Mha which are gap-filled from FRA 2020 (see Supplementary Tab. 3, and next section)

**The absolute flux is calculated by summing the absolute fluxes of the various categories (forest land, deforestation, organic soils, other).

Table 4. Statistics on land use categories reported in NGHGIs and used in this study. The % refers to the share within the categories (World, AI or NAI countries)

	n. of countries	**LULUCF**		**Forest land**		**Deforestation**		**Org. soils**		**Other**	
		n	%	n	%	n	%	n	%	n	%
World	195	185	95%	177	91%	122	63%	32	16%	85	44%
AI	43	43	100%	41	95%	39	91%	31	72%	36	84%
NAI	152	142	93%	136	89%	83	55%	1	1%	49	32%

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Table 5. Number of countries reporting on managed and unmanaged forest to UNFCCC (NGHGIs). For comparison and within the assumptions made in this paper, we also show country reporting to FAO (FAO, 2020) of secondary forest/plantation and primary forest area.

		managed	**secondary/ plantation**	**unmanaged**	**primary**
NGHGIs	AI	43		5*	
	NAI	107		4	
FRA	AI		43		26
	NAI		146		65

* including Canada, France, Greece, Russia, USA. All the other AI countries report that unmanaged forests do not occur.

Table 6. Countries where the difference between the net LULUCF CO_2 flux in the NGHGI DB and in the UNFCCC GHGDI is greater than 50 Mt CO_2/yr (absolute values, i.e. positive numbers indicate greater emissions or smaller sinks in the NGHGI DB than the UNFCCC GHGDI), and explanation of the different source used. Collectively, these countries explain most of the difference in global LULUCF values between the two datasets.

	Difference NGHGI DB vs. UNFCCC GHGDI (Mt CO_2/yr)	**Source NGHGI DB**	**Source UNFCCC GHGDI**	**Comment**
Central African Republic	1538	NDC 2016	NC2 2015	NDC 2016 used (Fig. 1, including both emissions and removals) because more recent than NC2 (2015). Note that a more recent NDC (2021) was ignored because the reported sink (-0.7 Gt CO_2/yr) is biophysically impossible.
Democratic Republic of the Congo	761	NDC 2021	NC3 2015	NDC 2021 used (Fig. 1) because more recent than the NC3 (2015) and broadly consistent with REDD+ (2018). However, this source does not report any carbon sink from forest.
Guinea	478	NDC 2021	NC2 2018	NDC 2021 used (Tab. 7) because more recent than the NC2 (2018), even if no forest sink is reported. Note that the sink in the NC2 is biophysically impossible (-0.4 Gt CO_2/yr over 5 Mha forest).
Nigeria	189	BUR2 2021	NC2 2014	BUR2 2021 used (Tab. 2.11) because more recent than the NC2 2014. Note that the NDC 2021 and BUR2 2021 report different numbers. Here the BUR is used because much more detailed.
Papua New Guinea	175	BUR1 2019	NC2 2015	BUR1 2019 used (Fig. 2.11) because more recent than the NC2 2015.

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Madagascar	173	REDD+ 2018	NC3 2017	REDD+ used (2018) because more recent than the NC3 (2017), but it covers only deforestation. Note that the NC3 reports a biophysically impossible sink (-0.3 Gt CO_2/yr over 9 Mha of forest).
Myanmar	147	REDD+ 2018	NC1 2012	REDD+ (covering DEF, ECS) used because NDC 2021 confirmed it as the correct source to look at.
Guyana	101	REDD+ 2015	NC2 2012	REDD+ (covering DEF, DEG), used because more recent than the NC2 (2012)
Zimbabwe	95	BUR1 2021	NC3 2017	BUR1 2021 used (based on Fig. 2.18) because more recent than the NC3 (2017) and more complete than NDC 2021 (where LULUCF values seem unclear)
Cambodia	88	REDD+ 2021	NC2 2016	REDD+ (including DEF, ECS) used because more recent than the NC2 (2016)
Thailand	70	REDD+ 2021	NC3 2018	REDD+ 2021 (including DEF, DEG, ECS) used because more recent and complete than the NC3 (2018)
Congo	64	NDC 2021	NC2 2009	NDC 2021 used (Tabs. 7 and 8) because more recent than the NC2 (2009)
Angola	54	NC2 2021	NC1 2012	NC2 2021 used (Tab. 2) because more recent that NC1 (2012)
Brazil	53	NC4 2020	BUR4 2020	NC4 2020 used (Appendix I) because more disaggregated and rich in information than BUR4 2020, even if not fully consistent (BUR4 has lower emission values).
Indonesia	-286	BUR3 2021	NC3 2018	BUR3 2021 used (Tab. 2.17) because more recent than NC3 2018 and more complete than REDD+ (2022).
Mexico	-184	NIR 2019	NC5 2012	NIR 2019 used (Tabs. 5.23-5.32) because more recent than the NC5 (2012) and more complete than REDD+ (2020)
Namibia	-117	NIR 2021	NC3 2015	NIR 2019 used (Tab. 6.18) because more recent the NC3 (2015) and than more complete than NDC 2021

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Table 7. Statistics on the number of NAI countries (and corresponding forest area) for which NGHGI DB and FAOSTAT compute null or non-null carbon fluxes for forest land (FL) and 'forest land remaining forest land' (FL-FL). To note is that FAOSTAT does not explicitly distinguish the two subcomponents of FL, i.e. FL-FL and land converted to forest (L-FL). Here, we performed an additional analysis based on the original country reports to FRA: if the country report to FRA includes a constant value of carbon stock/ha over time, then we assume that the carbon flux FL-FL is zero and that any value computed by FAOSTAT for FL comes from L-FL only (see text for details).

		NGHGI-DB		**FAOSTAT**	
		n. Countries	Area (Mha)	n. Countries	Area (Mha)
FL	Non-zero flux	136	1647	113	1859
	No or zero flux	16	272	39	327
FL-FL	Non-zero flux	136	1647	63	1282
	No or zero flux	16	272	89	905
Total		152	1919	152	2186

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Table 8. Assessment of the reasons for the difference between the NGHGI database and FAOSTAT for 152 NAI countries, based on the completeness/uncertainty in the estimates of Forest Land (FL) and Deforestation, and of carbon pools included. The method used is illustrated in Supplementary Figure 2. The total flux (-1651 Mt CO_2/yr) is the average difference, for the sum of FL and deforestation in NAI countries, between NGHGI DB (+79 Mt CO_2/yr) and FAOSTAT (+1819 Mt CO_2/yr) for the period 2000-2020.

	Countries		**Difference explained**	
	n	***%***	***Mt CO_2/yr***	***%***
NGHGI DB Countries where NGHGIs in our database appear either more complete, or report non-zero sinks on forest land, than FAOSTAT, and/or for the reporting of non-biomass carbon pools	73	48%	-605	37%
Uncertain Countries where both databases are incomplete, or countries where the NGHGIs in our database are considered implausible*, but for which FAOSTAT estimates a zero carbon flux for FL-FL.	52	34%	-706	43%
FAOSTAT Countries where FAOSTAT appear more complete for FL or Deforestation, or where the NGHGIs in our database are considered implausible* and FAOSTAT estimates a non-zero carbon flux for FL-FL.	27	18%	-340	21%
Total	152		-1651	

*Where the forest sink is greater than -10 tCO_2/ha over >1Mha, see Methods.

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FIGURE CAPTIONS

Figure 1. Global forest area reported to UNFCCC (as consolidated and gap-filled in the NGHGI DB) (managed and unmanaged) and FRA (primary and secondary + plantations) for the year 2015 at global level (a) and for five macro regions (b-f). For the NGHGI DB, about 1% of total forest area in NAI countries is gap-filled with FAO data (i.e., 2, 43 and 1 Mha in panels d, e and f, respectively).

Figure 2. Global trend 2000-2020 of CO_2 fluxes from the NGHGI DB for the various land uses and land-use change categories (a) and for Annex I vs. non-Annex I countries (b).

Figure 3. Trends 2000-2020 of LULUCF CO_2 fluxes from the NGHGI DB for the largest Annex I (a) and non-Annex I (b) countries (or country aggregations). Dots indicate the years for which the data exists in the original submission (i.e. not gap-filled).

Figure 4. Global trend 2000-2020 of CO_2 fluxes from our NGHGI DB and FAOSTAT for LULUCF (a), Forest land (b), Deforestation (c, corresponding to net forest conversion in FAOSTAT) and Organic Soils (d, including peat drainage and peat fires).

Figure 5. CO_2 fluxes (average 2000-2020) in Annex I and non-Annex I countries from our NGHGI DB and FAOSTAT, for LULUCF (a), Forest land (b), Deforestation (c, typically gross in NGHGIs and net in FAOSTAT) and Organic Soils (d, including peat drainage and peat fires).

Figure 6. CO_2 fluxes (average 2000-2020) in the five macro-regions from our NGHGI DB and FAOSTAT, for Forest land (a) and Deforestation (b, net deforestation in FAOSTAT). The numbers next to each column in panel a indicate the areas (in Mha, and % relative to the respective regional forest area) where no or zero

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Figure 7. Disaggregation of the differences in net global LULUCF CO_2 fluxes (average 2000-2020) between the NGHGI DB presented in this study and UNFCCC GHG Data Interface (UNFCCC GHGDI), and between the NGHGI DB and FAOSTAT, into different categories. For NAI countries, numbers for Forest Land (FL) and Deforestation (DEF) reflect the analysis shown in Table 8. Whiskers indicate the estimated global uncertainty (95% confidence interval) on the net LULUCF flux for the NGHGI DB (see Methods) and FAOSTAT (Tubiello et al. 2021). See text for details.

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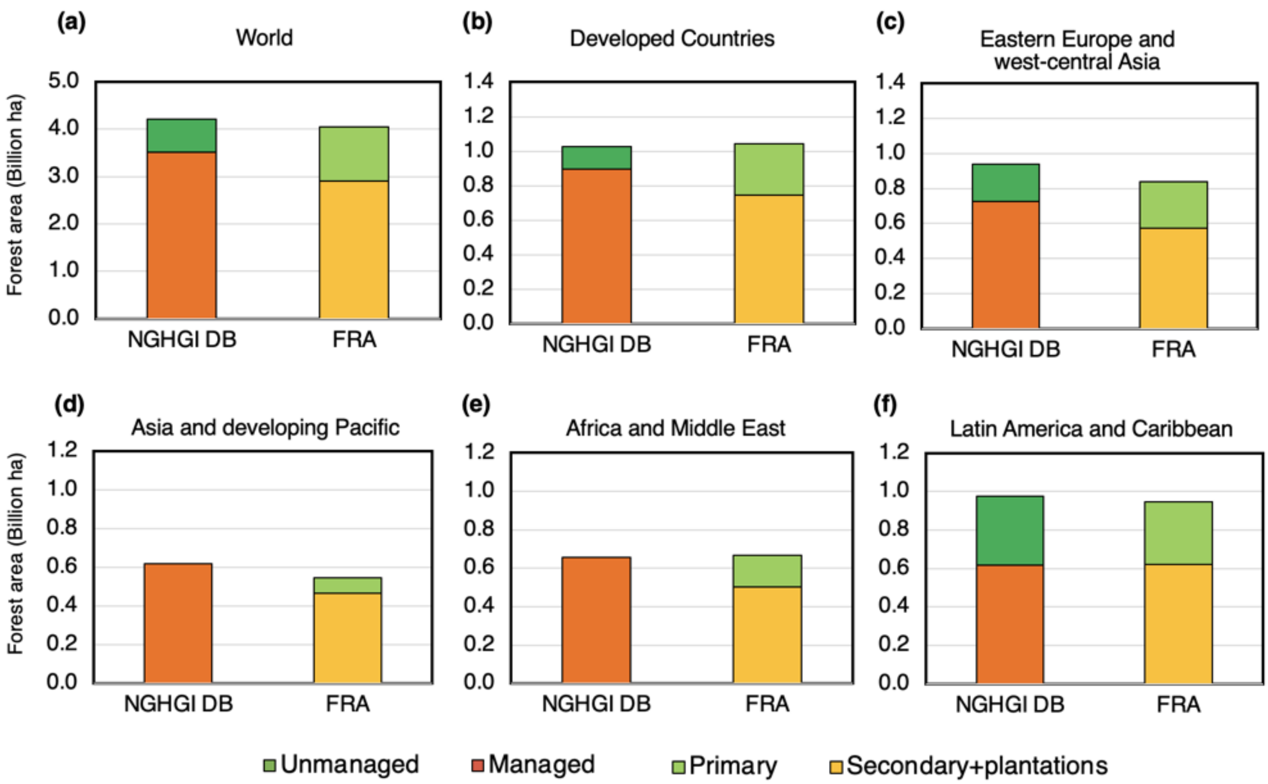
965 # FIGURES



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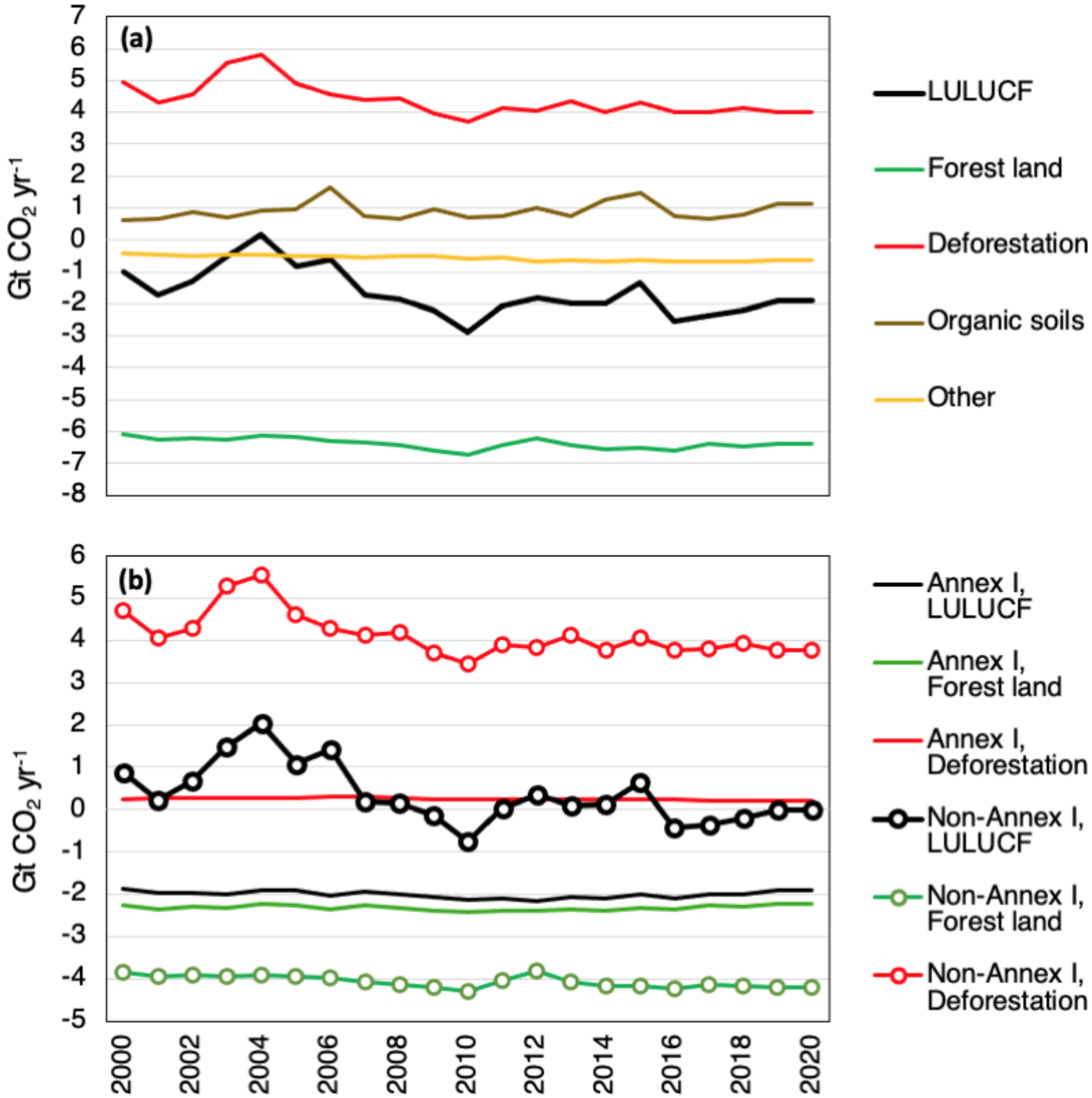

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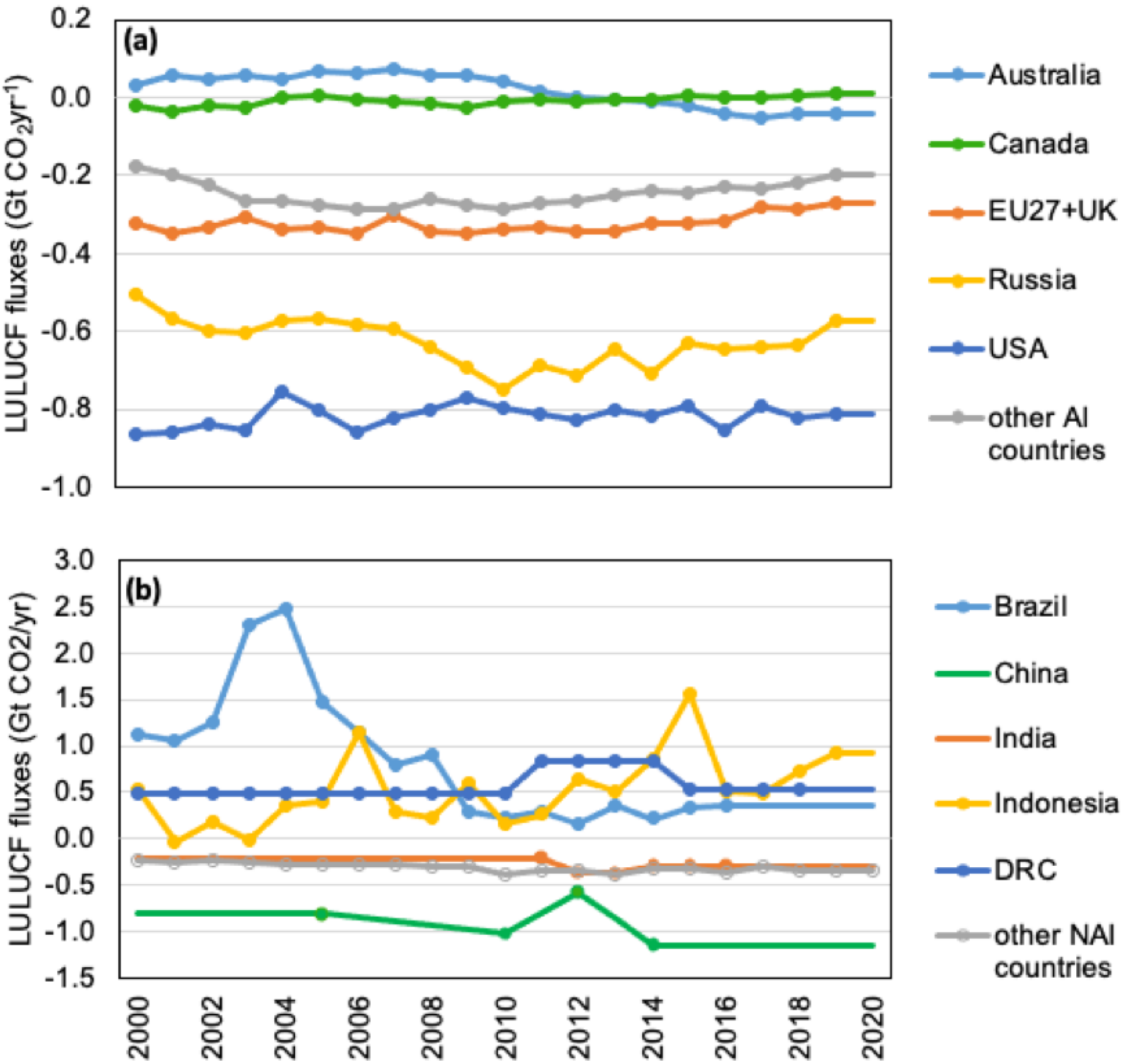

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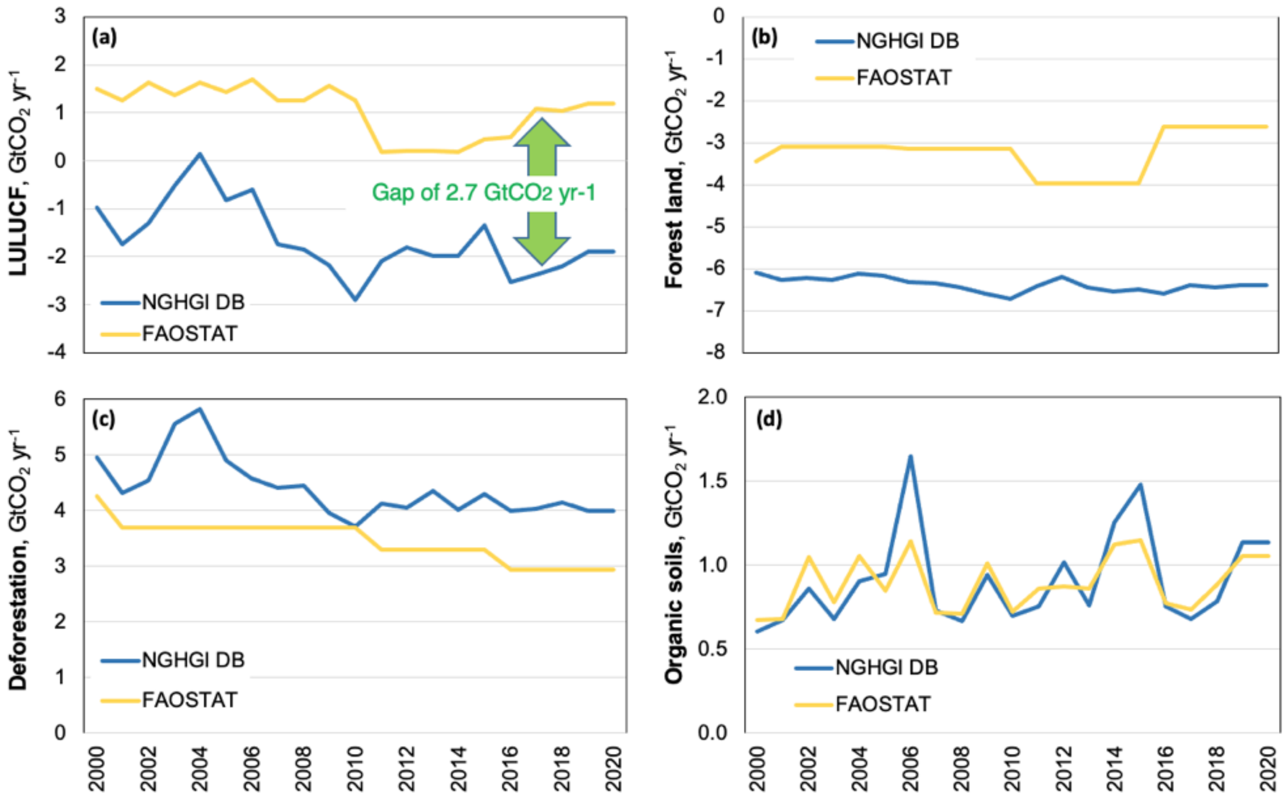

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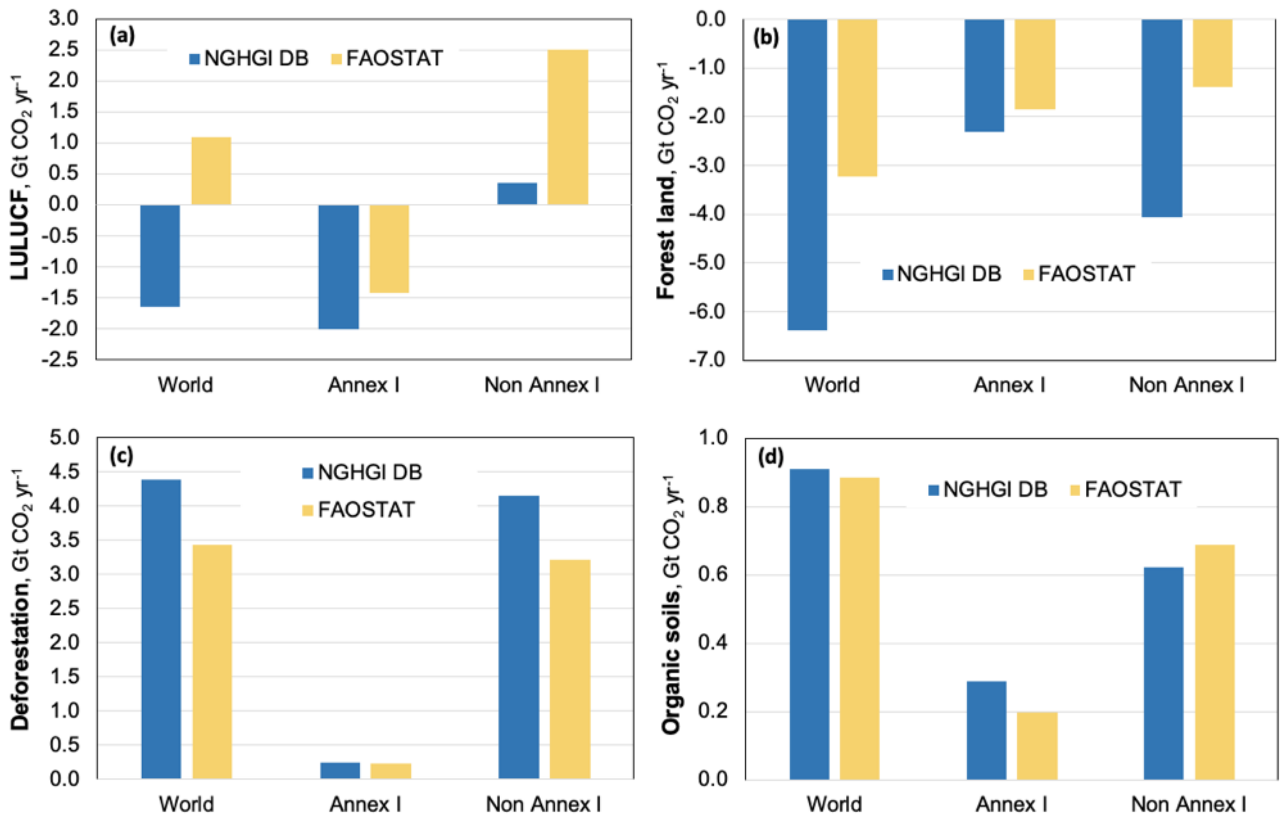

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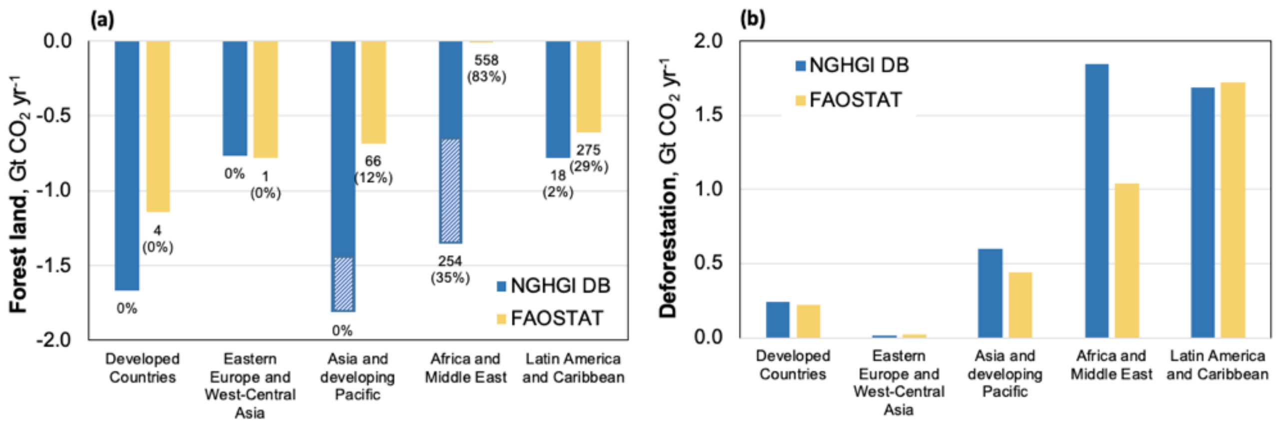

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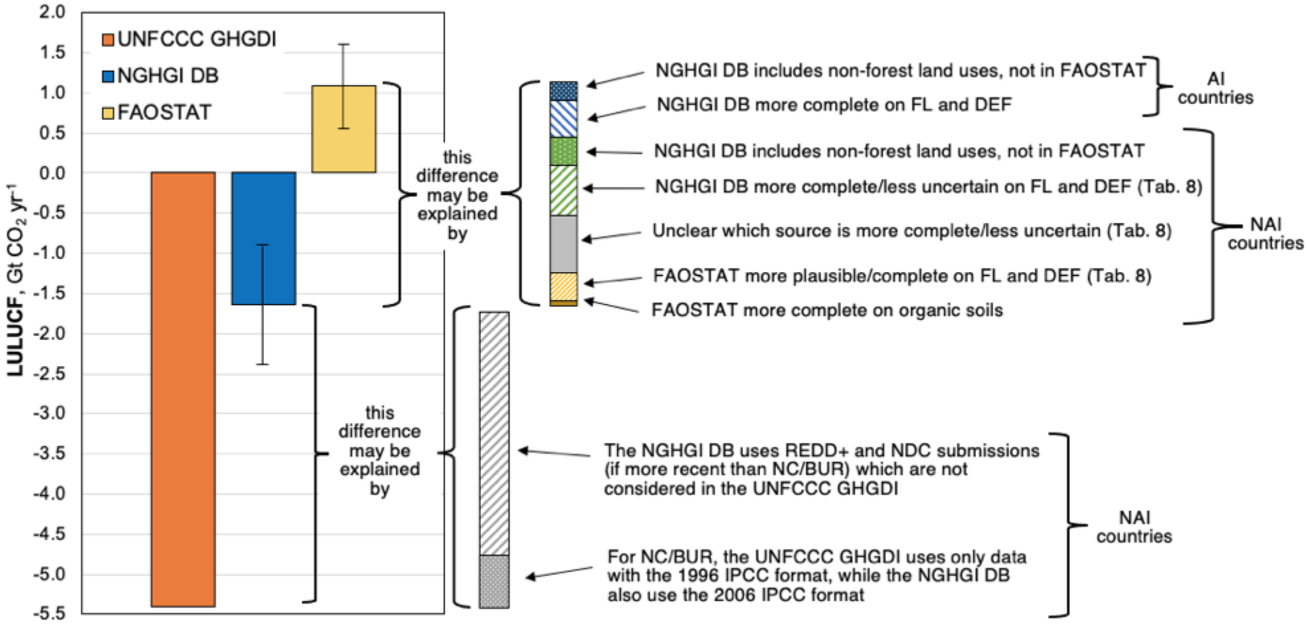

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