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Mapping land-use fluxes for 2001-2020 from global models to national inventories

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Abstract

With the focus of climate policy shifting from pledges to implementation, there is an increasing need to track progress on climate change mitigation at country level, especially for the land-use sector. Despite new tools and models offering unprecedented monitoring opportunities, striking differences remain in estimations of anthropogenic land-use CO_2 fluxes between the national greenhouse gas inventories (NGHGIs) used to assess compliance with the Paris Agreement, and the Global Carbon Budget and IPCC assessment reports, both based on global bookkeeping models (BMs).

Recent evidence showed that these differences are mainly due to inconsistent definitions of anthropogenic forest CO_2 fluxes. In particular, the part of the land sink that is caused by the indirect effects of human-induced environmental change (e.g., fertilization effect on vegetation growth due to increase atmospheric CO_2 concentration, climate change) on managed lands is treated as non-anthropogenic by BMs, while in most cases is considered anthropogenic in NGHGIs. In addition, countries use a broader definition of managed land than BMs.

Building on previous studies, we implement an approach that adds the CO_2 sink due to environmental change from countries' managed forest area (estimated by Dynamic Global Vegetation Models, DGVMs) to the original land-use flux from BMs. This sum is expected to be conceptually more comparable to NGHGIs. Our analysis uses updated and more comprehensive data from NGHGIs than previous studies and provides model results at a greater level of disaggregation in terms of land categories (i.e., forest land, deforestation, organic soils, other land uses) and countries.

Our results confirm a large difference in land use CO_2 fluxes between the ensemble mean of the BMs, estimating a source of 4.3 $GtCO_2$ yr^{-1} globally for the period 2001-2020, and NGHGIs, which estimate a sink of -1.7 $GtCO_2$ yr^{-1}. Most of this 6.0 $GtCO_2$ yr^{-1} gap is found on forest land (3.8 $GtCO_2$ yr^{-1}), with differences also for deforestation (1.1 $GtCO_2$ yr^{-1}), other land uses (1.0 $GtCO_2$ yr^{-1}), and to a lesser extent for organic soils (0.1 $GtCO_2$ yr^{-1}). By adding the DGVM ensemble mean sink arising from environmental change in managed forests (-5.1 $GtCO_2$ yr^{-1}) to BMs estimates, the gap between BMs and NGHGIs becomes significantly smaller both globally (residual gap: 0.9 $GtCO_2$ yr^{-1}) and in most regions and countries. The remaining differences mostly reflect smaller net emissions from deforestation and agricultural land in the NGHGIs of developing countries than in the BMs.

By reconciling most of the differences between NGHGIs and global models (BMs and DGVMs), offering a blueprint for operationalizing future comparisons, and identifying areas to be further investigated, this study represents an important step forward for increasing transparency and confidence in land-use CO_2 flux estimates at the country level. This is crucial to support land-based mitigation investments and assess the countries' collective progress under the Paris Agreement's Global Stocktake.

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Introduction

Over the last five years prior to the United Nations Framework Convention on Climate Change (UNFCCC) conference in Glasgow in 2021, most countries have submitted new or updated 2030 mitigation goals (UNFCCC 2022a, Meinshausen et al. 2022). Now, the focus of climate policy is progressively shifting to the implementation of these goals. As a result, there is an increasing interest in verifying and tracking the progress of climate change mitigation at the country level. The interest is particularly high in the land use, land-use change and forestry (LULUCF) sector, which represents about 25% of the emission reductions pledged by countries in their National Determined Contributions (NDCs) (Grassi et al., 2017), is recognized as a key factor to mitigate climate change (Roe et al., 2021; IPCC, 2022b) and is receiving increasing attention at policy level: at the UNFCCC conference of the Parties in Glasgow in 2021, 141 countries committed to collectively end forest loss and land degradation by 2030 (Taylor et al., 2021, Nabuurs et al. 2022, Gasser et al. 2022). However, the LULUCF sector is complex in terms of definitions and concepts, and in the measurements required for estimating greenhouse gas (GHG) fluxes. Despite new observation platforms, tools and models that offer unprecedented monitoring opportunities, striking differences remain between land-use CO_2 fluxes estimated by different approaches.

The Global Carbon Budget (Friedlingstein et al., 2022) uses Dynamic Global Vegetation Models (DGVMs) and global bookkeeping models (BMs) to estimate natural and anthropogenic CO_2 fluxes from land, respectively. These estimates are also used in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) (Canadell et al., 2021; IPCC, 2022b). DGVMs estimate that terrestrial ecosystems absorb nearly a third of the total anthropogenic CO_2 emissions (Friedlingstein et al. 2022), mainly in forests. BMs estimate that land use is a net source of CO_2 globally, mainly due to deforestation, equal to around 12% of total global anthropogenic CO_2 emissions. However, the national greenhouse gas inventories (NGHGIs) used to assess compliance with the Paris Agreement report a net anthropogenic sink of CO_2 for the LULUCF sector globally (Grassi et al., 2022). This discrepancy between estimates from global models (BMs and DGVMs) and NGHGIs is confusing for policymakers, and makes the estimates look very uncertain.

Previous studies (Grassi et al., 2018, 2021) suggested that most of the discrepancies between the NGHGIs and global models reflect differences in defining the drivers of CO_2 fluxes from land; in particular, how anthropogenic forest sinks and areas of managed land are defined. Identifying these drivers is challenging because natural and anthropogenic processes are complex and highly variable over space and time.

The IPCC Guidelines for NGHGIs (IPCC, 2006, 2019) distinguish three types of effects that can drive the fluxes between land and the atmosphere: (1) direct human-induced effects, i.e. land-use changes and management practices; (2) indirect human-induced effects, i.e. human-induced environmental changes (e.g., changes in atmospheric CO_2 concentration, nitrogen deposition, temperature, or precipitation) that affect growth, mortality,

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decomposition rates, and natural disturbances regimes; and (3) natural effects, including climate variability and a background natural disturbance regime.

Due to differences in purpose and scope, the largely independent scientific communities that support the IPCC Guidelines (reflected in NGHGIs) and those that support the IPCC assessment reports (based on global models) have developed different approaches to identify anthropogenic GHG fluxes, as illustrated in Figure 1. The main conceptual difference is that global models consider those forests as managed that were subject to recent harvest and have not yet regrown to pre-harvest stock level, whereas, consistent with IPCC guidelines (IPCC 2006), NGHGIs define managed forests more broadly (i.e., forests that fulfill social, economic and ecological functions, thus also including protected areas or areas with fire prevention activities). In this larger area, which is consistently reported over time, NGHGIs also generally consider most of the human-induced environmental changes as anthropogenic (see Methods), while the global model approach treats these changes as part of the non-anthropogenic, natural sink. Both approaches are broadly valid in their specific contexts but are not directly comparable. If the differences in land-use CO_2 fluxes between BMs and NGHGIs are not reconciled or transparently explained, they may jeopardize the confidence in the LULUCF mitigation potential, question fair burden-sharing of emissions reductions, and hamper an accurate assessment of the collective progress under the Paris Agreement's Global Stocktake.

- Figure 1-

Grassi et al. (2018) proposed a simple approach to reconciling these conceptual differences: building on a post-processing of global model results, the fluxes from secondary forest from nine DGVMs were added to the fluxes from one BM. Grassi et al. (2021) used a more refined approach to reconcile the gap between NGHGIs and five Integrated Assessment Models (IAMs, used to estimate future emission pathways with the same definition of land-use fluxes as BMs), i.e. the sink estimated by DGVMs over non-intact forests - used as proxy for managed forest in NGHGIs - was added to IAMs' results. This refined approach was also included in the Global Carbon Budget 2021 (Friedlingstein et al., 2022) to reconcile the difference in global land-use estimates between BMs and NGHGIs. The original results from three BMs were adjusted by adding the average CO_2 sink occurring in the area of non-intact forest, estimated from 17 DGVMs (table A8, Friedlingstein et al., 2022). The findings and recommendations from Grassi et al. 2021, i.e. that adjustments should be made whenever a comparison between LULUCF fluxes reported by countries and the global emission estimates of the IPCC is attempted, are reflected in the work of the IPCC Sixth Assessment Report (e.g., box 3 in Chapter 3 and box 6 in Chapter 7, IPCC, 2022a) and in UNFCCC reports of high policy relevance, such as the Synthesis report of NDCs (UNFCCC, 2021) and the Synthesis report for the technical assessment component of the first Global Stocktake (UNFCCC, 2022b). In the absence of these adjustments, collective progress under the Global Stocktake, based on NGHGIs, would appear better than it is.

The present study illustrates and discusses in more detail the reconciliation between BMs and NGHGIs that was shown in brief in Friedlingstein et al. (2022). The analysed period is 2001-2020. The specifics include slight

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updates in the method and a greater level of disaggregation in terms of land categories (forest land, deforestation, organic soils, other land uses), regions and countries. Specifically, we test the hypothesis that, when land-use fluxes by global models are made conceptually more comparable to NGHGIs, most of the previous large differences are reconciled globally as well as regionally and for large countries. This is of major importance as the different definitions of the anthropogenic CO_2 sink (i.e. global models vs. NGHGIs) may have implications for a fair and realistic allocation of mitigation targets across countries (Schwingshackl et al., 2022).

While this study focuses on the reconciliation of the main conceptual difference between BMs and NGHGIs, it should be noted that other differences exist, mentioned in the methods and the discussion. Here we focus on the reconciliation of fluxes and on identifying any remaining large discrepancy between the adjusted BM results and NGHGIs. Furthermore, we discuss our results in the context of the Global Carbon Budget and outline a way forward to support a more robust operationalization of the comparison between global models and NGHGIs. The aim is to increase the confidence in land-use fluxes reported by NGHGIs, which is useful to foster investments in LULUCF mitigation and to assess the collective progress under the Paris Agreement's Global Stocktake.

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Methods

Global models

Two fundamentally different types of global models are used to simulate the CO_2 exchange between the terrestrial biosphere and the atmosphere (Friedlingstein et al., 2022): bookkeeping models (BMs) and dynamic global vegetation models (DGVMs).

BMs track changes in the carbon stocks of areas undergoing land-use and land cover change using predefined rates of growth and decay for broad types of vegetation and soil carbon. Here we use the results for 2001-2020 from the three BMs used in Friedlingstein et al. 2022: BLUE (Hansis et al., 2015), OSCAR (Gasser et al., 2020), and H&N (Houghton and Nassikas, 2017). The net CO_2 flux from BMs (land-use change emissions, E_{LUC}, in Friedlingstein et al., 2022) includes CO_2 fluxes from deforestation, afforestation, harvest activity, shifting cultivation, regrowth of forests and other natural vegetation-types following wood harvest or abandonment of agriculture, and transitions between other land types. Typically, BMs tend to limit the rate and maximum biomass of post-harvest regrowth up to the pre-harvest carbon stock levels. Emissions from peat burning and peat drainage are added from external datasets. BMs generally do not include the CO_2 fluxes associated with natural disturbances.

DGVMs simulate ecosystem processes (primary productivity, autotrophic and heterotrophic respiration), their response to changing CO_2, climate, anthropogenic land-cover changes, and, depending on the model, additional processes such as management, nitrogen inputs and some natural disturbances, as well as natural land cover changes (Sitch et al., 2015). Within these models, the anthropogenic fluxes are quantified by taking the difference between model simulations (started in pre-industrial times) with and without land-cover change.

In this study, the natural terrestrial CO_2 fluxes from 17 DGVMs are considered, derived from the same model run as used in Friedlingstein et al. 2022 (S2 run, with CO_2 and climate change only, i.e., without land-use change since pre-industrial times, and denoted as S_{LAND}). The anthropogenic fluxes in this study originate from the BMs, which allow observation-based data, such as carbon densities of different biomes, to be included and therefore, implicitly, have a more complete representation of land management processes than DGVMs. For example, in BMs primary and secondary ecosystems may have different carbon densities to reflect degradation processes, and the observation-based soil carbon estimates for cropland implicitly capture all land management processes such as tillage, fertilization and harvesting - processes that only some DGVMs have implemented. However, by not representing such land management activities in a process-based way, BMs represent average values (e.g. country- or biome-averages) rather than distinguishing different levels of intensification or specific forms of management, such as forest thinning from above or below. In addition, the anthropogenic CO_2 emissions by DGVMs are not directly comparable to BM estimates of land-use change emissions or any observable carbon fluxes because they account for the 'loss of additional sink capacity' (i.e., the difference

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between the actual land sink under changing land-cover and the counterfactual land sink under pre-industrial land-cover, Gasser and Ciais, 2013; Pongratz et al., 2014, Obermeier et al. 2021), a component of the carbon budget that poses another important issue for the comparison between global models and NGHGIs.

National Greenhouse Gas Inventories (NGHGIs)

The UNFCCC requires Parties to report NGHGIs of anthropogenic GHG emissions and removals. At present, this obligation differs for Annex I Parties (AI, advanced economies with annual GHG reporting commitments under the UNFCCC) and non-Annex I Parties (NAI, countries with less stringent reporting commitments), but a more harmonized reporting under the Paris Agreement is expected through Biennial Transparency Reports starting by the end of 2024.

In this study, we use the most up-to-date and complete compilation of LULUCF CO_2 data based on country submissions to UNFCCC (Grassi et al., 2022), openly available at https://doi.org/10.5281/zenodo.6390739. This database builds on a detailed analysis of a range of country reports to the UNFCCC, which include anthropogenic emissions and removals estimated following the IPCC methodology (IPCC, 1996, 2006). The CO_2 flux database is complemented by information on managed and unmanaged forest areas as available in NGHGIs submitted to the UNFCCC. Specifically, for AI countries, data are from annual GHG inventories. For NAI countries, the most recent and complete information was compiled from different sources, including National Communications, Biennial Update Reports, submissions to the framework REDD+ (Reducing Emissions from Deforestation and Forest Degradation), and NDCs. The data are disaggregated into fluxes from forest land, deforestation, organic soils, and other sources (Table 1). This database includes LULUCF data from 185 countries, covering 99.9% of the global forest (i.e., the land use category for which countries report the vast majority of the emissions and removals). To ensure a complete time series from 2001 to 2020, which is often not yet available in NAI countries, gaps were filled without altering the levels and trends of the country-reported data. Overall, while the quality and quantity of the LULUCF data submitted by countries to the UNFCCC significantly improved in recent years, important gaps and areas of improvement still remain. Yet, these gaps are expected to be progressively filled under the Paris Agreement Transparency Framework reporting. Most NAI countries still do not explicitly separate managed vs. unmanaged forest land, a few report implausibly high forest sinks or inconsistent estimates among different reports, and several report incomplete estimates (especially in Africa, where many countries still have low national capacity for reporting). For more details, including a discussion of the differences between the NGHGI database, the UNFCCC GHG data interface (UNFCCC, 2022b), and the FAOSTAT Land use emission database (Tubiello et al., 2021), see Grassi et al. (2022).

Due to the impossibility of providing widely applicable methods to disentangle direct and indirect human-induced effects and natural effects on land GHG fluxes through direct observations (e.g., national forest

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inventories), the IPCC Guidelines adopted the 'managed land' proxy (IPCC, 2006, 2010, 2019) as a pragmatic approach to facilitate NGHGI reporting. Anthropogenic land GHG fluxes (direct and indirect effects) are defined as all those occurring on managed land, i.e. where human interventions and practices have been applied to perform production, ecological or social functions. GHG fluxes from unmanaged land are not reported because they are assumed to be non-anthropogenic. The specific land processes included in NGHGIs depend on the estimation method used, which differs in approach and complexity among countries. A previous study (Grassi et al., 2018) concluded that most countries report both direct and most of the indirect anthropogenic effects on managed forests. Indirect effects are included especially when the stock-difference approach or recent forest growth factors are used to estimate net emissions and removals. With regard to natural disturbances, such as fires, insects and wind throws, these are included in most NGHGIs with the exception of Canada and Australia. Following the IPCC guidelines (IPCC 2019), these two countries implement a 'second-order approximation' for anthropogenic CO_2 fluxes (in principle, a refinement of the managed land proxy) and exclude the GHG emissions and subsequent CO_2 removals that are considered to result from natural disturbances from their NGHGIs. Overall, the average net emissions that were excluded from the NGHGI for the period 2001-2020 amounted to about 104 $MtCO_{2eq}$ yr^{-1} in Canada (Canada, 2021) and 39 $MtCO_2$ yr^{-1} in Australia (Australia, 2021).

While the different approaches to include direct and indirect anthropogenic effects represent the main conceptual difference between NGHGIs and global models, other differences exist as well. For example, differently from BMs, the IPCC methodological guidance does not assume that post-harvest forest regrowth is limited up to the pre-harvest C stock levels. In NGHGIs, these levels might be exceeded not only due to the impact of indirect anthropogenic effects but potentially also due to improvements in management practices that stimulate higher productivity. These improvements may lead to greater biomass density due to direct effects not explicitly simulated by BMs (e.g., Erb et al. 2013, Kauppi et al. 2020), for example, greater site fertility (due to discontinued litter ranking), selection of trees with higher growth rates or stocking density, or a better-regulated competition among trees (due to thinning).

- Table 1-

The majority of countries use the net land CO2 flux reported in NGHGIs to assess compliance with their NDCs and track progress of their long-term (i.e., 2050) emission reduction strategies. However, some countries expressed the intention to apply specific accounting rules to these estimates. These rules aim to better quantify the impact of additional mitigation actions on the land net CO2 flux by, for example, discounting the impact of natural disturbances and forest age-related dynamics (Kurz et al., 2018; Grassi et al., 2018; IPCC 2019). Under the Paris Agreement, countries are allowed to decide upon their own accounting rules, and this has sometimes led to a lack of clarity in the land contribution toward the NDCs (Fyson and Jeffery, 2019). Since this study focuses on the estimated CO2 fluxes, we consider the estimates reported in NGHGIs in their managed land irrespective of their potential future filtering through accounting rules.

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Approach to reconcile global models and national GHG inventories

We apply an approach similar to the one described by Friedlingstein et al. (2022) to map the global models' results to NGHGIs, with slight updates and a different disaggregation of the results to allow a more detailed comparison with NGHGIs.

Building on previous studies (Grassi et al., 2018, 2021), we added the natural CO_2 sink (S_{LAND} in Friedlingstein et al. 2022) in countries' managed forest areas to the direct anthropogenic land-use flux estimates from BMs (E_{LUC}) for the period 2001-2020. S_{LAND} is the sink due to indirect human-induced effects estimated by DGVMs, which includes the effects from increasing atmospheric CO_2 and climate change. To determine S_{LAND} in managed forests, the following steps were taken: Spatially gridded data of "natural" forest Net Biome Production (NBP = S_{LAND}) were obtained from the TRENDY v10 S2 runs of 17 DGVMs performed for the Global Carbon Budget 2021 (Friedlinstein et al., 2022) for the period 2001-2020. S2 runs include time-varying changes in climate and atmospheric CO_2 concentrations but exclude land-use changes. The results were first masked with the Hansen forest map (Hansen et al., 2013), with a 20% tree cover threshold and following the FAO definition of forest (isolated pixels with maximum connectivity less than 0.5 ha are excluded), and then further masked with a map of "intact" forest for the year 2013, i.e. forest areas without detected signs of human activity via remote sensing (Potapov et al., 2017) (Figure 2a). This way, we obtained S_{LAND} separately for "intact" and "non-intact" forest areas, which for most countries are a fairly good proxy for "unmanaged" and "managed" forest areas in the NGHGIs (see Supplementary Table 1). Consistently with Grassi et al. 2022b, we considered only the impact of indirect effects in forest areas, because most of the land sink occurs on forests, non-forest land is scarcely reported in the NGHGIs of NAI countries, and at present no reliable proxy for managed land exists for non-forest land uses.

At the global level, NGHGIs indicate about 3.7 and 0.7 Billion ha of managed and unmanaged forest, respectively. In comparison, the areas of non-intact and intact forest are about 3.2 and 0.9 Billion ha, respectively. An update compared to Friedlingstein et al. (2022) is that for Canada and Brazil, two countries with large areas of unmanaged forest, this study uses the national gridded map used in the respective NGHGIs (Canada, 2021; Brazil, 2020) instead of the intact/non-intact forest map of Potapov et al. (2017) (Figure 2). This approach is expected to further increase the comparability of the model-based fluxes with the NGHGIs of these two countries, as, for example, in Brazil the map of non-intact forests underestimates the area of managed land (because the NGHGI managed forest areas comprise protected areas and indigenous lands). Considering the national forest maps of Canada and Brazil, the global areas of non-intact and intact forest amount to about 3.3 and 0.8 Billion ha, respectively. Other countries with large areas of unmanaged forest (e.g., Russia and the Democratic Republic of Congo, DRC) do not provide maps of managed forests in their NGHGIs. For Russia, the non-intact forest map we used (0.61 Billion ha) underestimates the area of managed forest reported in the

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NGHGI (0.69 Billion ha), while for DRC the non-intact forest area matches well with the area reported in the NGHGI (both yielding 0.15 Billion ha). Our approach underestimates the area of managed forest also in Australia, where the NGHGI considers the whole forest area as managed (0.13 Billion ha, although a large part is assumed to be in carbon equilibrium), while the area of non-intact forest we used is 0.04 Billion ha (see Supplementary Table 1). At the global level, the area of managed forest we used accounts for about 80% of global forest area (Figure 2b). This figure is consistent with other studies also indicating that about 80% of global land area is under some form of human management (e.g., Erb et al. 2017, Ellis et al. 2021).

Furthermore, in order to facilitate the comparison of BM results with NGHGIs for specific regions and countries, our analysis provides far more detail than Friedlingstein et al. (2022), both in terms of disaggregation of estimates for specific land categories (Table 1) and trends.

-Figure 2-

Some methodological aspects should further be noted. First, of the 17 DGVMs used here, only 5 (CABLE-POP, CLASSIC, JSBACH, OCN, and YIBs,) had forest NBP at grid-cell level. One model (ISBA-CTRIP) provided forest NEP and simulated disturbances at pixel level that were used as a basis, in addition to forest cover fraction, to estimate forest NBP. For the other 11 DGVMs, when a grid cell had a forest, all the NBP per area was allocated to the forest. Results from these 11 DGVMs (net sink in non-intact forest) were not significantly different from the other DGVMs.

Second, using intact/non-intact maps for the year 2013 may lead to over- or underestimations of the managed forest area before or after 2013. However, since the net loss of total forest area in the period of our study (2001-2020) is very small compared to the total forest area in 2015 (around 2%), we can reasonably assume that the impact of our approach on the possible under- or over-estimation of the managed forest area (and the corresponding S_{LAND}) is minor.

Third, by filtering the S2 runs from DGVMs with the intact/non-intact forest layer of the year 2013, our analysis excludes areas where forest cover has been lost historically at the cost of agricultural areas. Therefore, the sink simulated by S2 runs, using a only hypothetical pre-industrial forest cover (the counterpart to the ‘loss of additional sink capacity’ included in the estimates of E_{LUC}), which is included in the S_{LAND} estimates by Friedlingstein et al. (2022), should not confound our analysis.

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Results and discussion

Quantifying the gap

While the difference in anthropogenic land-use CO_2 fluxes between global models and NGHGIs was discussed in other recent studies (Grassi et al. 2018, Grassi et al. 2021, Friedlingstein et al. 2022, Schwingshackl et al., 2022), the results presented here represent both an update based on data from the NGHGIs submitted in 2021, as well as an unprecedented level of disaggregation in terms of land categories (forest land, deforestation, organic soils, other), trends, regions, and countries. This disaggregation enables us to attribute more precisely the remaining gap to different approaches and categories.

When the average net land-use CO_2 flux for 2001-2020 of the three BMs (4.3 $GtCO_2$ yr^{-1}) is compared to NGHGIs (-1.7 $GtCO_2$ yr^{-1}), a gap of about 6.0 $GtCO_2$ yr^{-1} emerges from our study (Figure 3a). Most of the difference between BMs and NGHGIs is found on forest land (3.8 $GtCO_2$ yr^{-1}, Fig. 3b), but discrepancies emerge also for deforestation (1.1 $GtCO_2$ yr^{-1}, Fig. 3c) and other fluxes (1.0 $GtCO_2$ yr^{-1}, Fig. 3e). By contrast, the difference for organic soils, which are added to the BM estimates from external datasets (see Table 1), is small (0.1 $GtCO_2$ yr^{-1}, Fig. 3d). In general, trends are quite similar between BMs and NGHGIs.

Forest land and deforestation are the categories where the spread among BMs is greatest, with H&N showing smaller absolute values of forest sink and emissions from deforestation than OSCAR, while BLUE has intermediate values. The differences are largely the result of different rates of deforestation and different estimates of carbon densities for the forests affected, and partly due to different allocation of emissions associated with shifting agriculture.

-Figure 3-

The LULUCF flux gap between BMs and NGHGIs identified here is similar to the 5.5 $GtCO_2$ yr^{-1} previously found between Integrated Assessment Models (IAMs, whose approach to estimating the anthropogenic land-use CO_2 flux is similar to BMs) and NGHGIs (Grassi et al., 2021). However, the updates presented here shifted the values downwards, i.e. smaller net emissions in BMs (due to updates in the land use dataset used as input for BM simulations, see Friedlingstein et al. 2022), and a greater net sink in NGHGIs (due to more complete reporting by NAI countries, Grassi et al., 2022), and made the trends more similar (Figure 4).

-Figure 4-

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Towards reconciling estimates between global models and national GHG inventories

The forest sink that DGVMs attribute to the natural response of land to human-induced environmental change (S_{LAND}) has been split into the parts occurring in non-intact (managed) and intact (non-managed) forests (Figure 5a). In the absence of country maps of managed forests (which we could only obtain for Canada and Brazil), we use the intact/non-intact forest map as a proxy for unmanaged/managed forests (see Methods, and Supplementary Table 1). Three-quarters of the global forest sink (-6.5 $GtCO_2$ yr^{-1} for the period 2001-2020) occur in non-intact (managed) areas, which similarly represent about three-quarters of the ~4 Billion ha of world's forests (Figure 2b). On average across the globe, net S_{LAND} per unit area appears very similar between intact and non-intact forests (-1.6 tCO_2 $ha^{-1}yr^{-1}$).

In this study, we use the average S_{LAND} in non-intact forest from 17 DGVMs models (-5.1 $GtCO_2$ yr^{-1} globally for the period 2001-2020, see Figure 5b) as a proxy for the sink from indirect human-induced effects in managed forest (see Figure 1), which is assumed to be included in the vast majority of NGHGIs. While exceptions to this assumption exist - e.g. the methods used by Australia and Canada imply that only a part of these indirect effects is included in their NGHGIs - the available information indicates that the majority of countries report most of the indirect human-induced effects on their managed land (Grassi et al., 2018).

The adjustment estimated by Grassi et al. (2021), using one DGVM only, was equal to -5.0 $GtCO_2$ yr^{-1} for the period 2005-2020 (Supplementary Table 8, Grassi et al. 2021). For the same period, the adjustment estimated here is -5.3 $GtCO_2$ yr^{-1}. The similarity confirms that the adjustment applied by Grassi et al. 2021 to future IAM emission pathways, even if derived only from a single model, was well representative of the ensemble mean. In both cases, the adjustments reconcile most of the gaps identified between the anthropogenic land-use CO_2 flux estimated by NGHGIs and by global models (either IAMs or BMs). The remaining gaps – i.e., about -0.5 $GtCO_2$ yr^{-1} in Grassi et al. (2021) for 2005-2020, and -0.9 $GtCO_2$ yr^{-1} in this study for 2000-2020 – are well within the uncertainty of the respective datasets (e.g. see the large variability of DGVM estimates in Figure 5b).

-Figure 5-

Our estimates of S_{LAND} in intact/non-intact forests are not affected by the assumption of a pre-industrial forest distribution because the related carbon sinks due to historical environmental changes in such hypothetical forest areas are not included (see Methods). These carbon sinks result from the 'loss of additional sink capacity' that the E_{LUC} estimates from DGVMs by Friedlingstein et al. (2022) include, which amounts to about 2.5-3.1 $GtCO_2$ yr^{-1} in recent years (Gasser et al. 2020, Obermeier et al., 2021). This helps explain why the S_{LAND} that we consider for the period 2001-2020, i.e. -6.5 $GtCO_2$ yr^{-1} estimated by DGVMs to occur in present-time forest area, is considerably smaller than the S_{LAND} values in table 5 from Friedlingstein et al. (2022), i.e. -10.4 $GtCO_2$ yr^{-1}, which are estimated by DGVMs for all terrestrial ecosystems and include the carbon fluxes on forest areas that had been cleared over the industrial era.

If the sink from non-intact forest is added to the original results from BMs, the adjusted results for LULUCF match much better with the sum of NGHGIs (Figure 6a). At the same time, this adjustment leads to a forest sink that is higher for the adjusted BMs compared to NGHGIs (Figure 6b). Overall, these findings suggest that the conceptual difference in defining the anthropogenic forest sink (BMs versus NGHGIs) explains most of the gap but not all. To gain more insights into the remaining differences, we compare below the results from BMs and NGHGIs for individual land use categories at global, regional, and country-level.

-Figure 6-

For LULUCF, the match between BMs and NGHGIs improves considerably after the adjustments both at the global level - where the original gap is reduced from 6.0 $GtCO_2$ yr^{-1} to 0.9 $GtCO_2$ yr^{-1} – and for AI and NAI countries (Figure 7a). While the same pattern is confirmed for most of the regions and countries analyzed (Figures 7b and 7c), in some cases, the adjustment does not help to close the gap (Canada, Brazil, Democratic Republic of Congo (DRC)), as also noted by Schwingshackl et al. (2022). Furthermore, after the adjustment, a large discrepancy remains in Asia, with BMs + DGVMs estimating higher net emissions than NGHGIs (including in China and India). At the global level, this discrepancy is partly compensated by differences in the opposite direction in Africa and Latin America, where BMs + DGVMs estimate lower net emissions than NGHGIs.

-Figure 7-

Disaggregating the LULUCF fluxes into four main land categories (Figure 8), the forest sink in the adjusted BMs is higher than in NGHGIs for NAI countries, but not for AI countries (except for Canada). While some NAI countries report implausibly high estimates of the forest sink (Central African Republic, Mali, Namibia, Malaysia, and Philippines), others do not report any estimate of the sink in forest land (e.g. DRC, Tanzania, Mozambique, Guyana), with the two effects likely approximately compensating (Grassi et al., 2022). In addition, not all NGHGIs include all recent indirect human-induced effects (e.g., due to CO_2 fertilization), and thus may underestimate the forest sink relative to the adjusted estimates from BMs.

For deforestation, organic soils, and other fluxes, the match between BMs and NGHGIs is reasonable for AI countries (< 0.1 $GtCO_2$ yr^{-1} gap for each category), while a larger gap is found for NAI countries (1.0 $GtCO_2$ yr^{-1} for deforestation, 0.2 $GtCO_2$ yr^{-1} for organic soils and 0.9 $GtCO_2$ yr^{-1} for other). The greater differences for NAI countries may be due to a far less complete reporting in NGHGIs compared to AI countries.

-Figure 8-

A more detailed disaggregation of the results by region and large countries is illustrated in Figure 9, and more complete results by country are provided in Supplementary Table 1.

-Figure 9-

For forest land, the adjustment of including natural fluxes in non-intact forests improves the match between BMs and NGHGIs in most regions except in Latin America, where the adjusted estimates from BMs result in a

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higher sink than NGHGIs (Figure 9a). Yet, even where the regional match for forest land is good, some discrepancies remain at the country level (Figure 9b). In Canada, for example, while the original BMs result is close to the NGHGI, the adjusted one yields a much larger sink (by 0.33 $GtCO_2\ yr^{-1}$). This may be explained at least in part by the fact that Canada uses empirical growth and yield curves compiled over decades from thousands of sample plots. While environmental change (e.g., climate and CO_2 forcing) enhance tree growth over time, empirical yield curves represent average growth rates measured over decades, therefore not fully including the recent impact of indirect human-induced effects – an approach that is conceptually similar to the original BM results. In Asia, the main discrepancies are observed in Indonesia (0.23 $GtCO_2\ yr^{-1}$) and Myanmar (0.18 $GtCO_2\ yr^{-1}$), where the unadjusted forest sink of BMs (in particular BLUE and OSCAR) is much greater than the NGHGI sink. On the other hand, for China, BMs estimate a much smaller sink than the NGHGI (by 0.33 $GtCO_2\ yr^{-1}$), also after the adjustment. This difference is especially large for BLUE and OSCAR, and is likely mostly due to the fact that these two models use a land-use change map (LUH2, Hurtt et al. 2020) that does not fully capture the large-scale afforestation in China (Schwingshackl et al., 2022), and which on the contrary is reflected in the country statistics used in NGHGIs and in H&N. In Africa, the good match at the regional level masks large country-level differences in opposite directions (see Supplementary Table 1). For example, the sum of BMs and DGVMs gives a large sink in the non-intact forest in DRC (0.42 $GtCO_2\ yr^{-1}$) - while this country does not provide an estimate of forest land - and a smaller sink in the Central African Republic (by 0.24 $GtCO_2\ yr^{-1}$). In Latin America, the large forest sink by BMs + DGVMs compared to the NGHGIs are mostly in Brazil (0.24 $GtCO_2\ yr^{-1}$) and in Colombia (0.16 $GtCO_2\ yr^{-1}$). In Colombia, BLUE and OSCAR estimate a forest sink much greater than the NGHGI also before the adjustment.

The natural forest sink estimated by DGVMs, which is the same in intact and non-intact forests when expressed on an area basis, overall compares well with the net sink estimated from ground plots of intact old-growth tropical forests (Hubau et al. 2020). Specifically, Hubau et al. (2020) estimated a net sink of about -2.2 $tCO_2\ ha^{-1}\ yr^{-1}$ in Africa (2000-2015) and -1.5 $tCO_2\ ha^{-1}\ yr^{-1}$ in the Amazon (in 2000-2011), while DGVMs estimated a net sink of -1.8 $tCO_2\ ha^{-1}\ yr^{-1}$ in Africa and -1.9 $tCO_2\ ha^{-1}\ yr^{-1}$ in the Amazon in the same period (although with large variability among models, see Figure 5b). The potential overestimation of the sinks in Africa and the Amazon by DGVMs could explain part of the remaining difference between the adjusted BM results and NGHGIs in countries like Brazil and Colombia.

For deforestation, regional results from BMs broadly agree with NGHGIs except in Asia and Africa (Figure 9c). In Asia, BMs estimate higher emissions in Indonesia (by 0.50 $GtCO_2\ yr^{-1}$), China (by 0.23 $GtCO_2\ yr^{-1}$), Myanmar (by 0.15 $GtCO_2\ yr^{-1}$), India (by 0.12 $GtCO_2\ yr^{-1}$) and Vietnam (by 0.11 $GtCO_2\ yr^{-1}$). By contrast, in Africa, BMs estimate smaller emissions than NGHGIs in Nigeria (by 0.22 $GtCO_2\ yr^{-1}$), Central African Republic (by 0.09 $GtCO_2\ yr^{-1}$), and DRC (by 0.07 $GtCO_2\ yr^{-1}$) (Supplementary Table 1). In Latin America, BMs estimate smaller emissions in Brazil (by 0.25 $GtCO_2\ yr^{-1}$). It should be noted that the separation of CO_2 fluxes between forest land and deforestation may be done differently by BMs and NGHGIs, e.g. shifting cultivation may be counted

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in different categories. For this reason, a better match between BMs + DGVMs and NGHGIs is often obtained if these two categories are combined (e.g., in Asia).

For organic soils, results from BMs broadly agree with NGHGIs except in Asia, mainly due to differences in China, where the NGHGI does not separately report this category.

In the category 'other' (cropland, grassland, wetlands, settlements; i.e. land uses that are more poorly included in NGHGIs in general), the large difference in Asia is mainly due to a large sink in agricultural lands reported by India and China, whereas BMs report a source for these countries. While this may be partly due to the fact thatBMs estimate only land-use changes for agricultural lands (e.g., grassland conversion to cropland and not 'cropland remaining cropland'), the large sinks reported by India (for cropland) and China (for cropland, grassland, and wetlands) are not well documented. BMs report greater emissions than NGHGIs in Africa and Latin America, presumably mainly due to the incomplete reporting of these categories in NGHGIs. For the USA, the greater sink from the NGHGI compared to BMs is partly explained by the large sink reported in settlements (-0.13 $GtCO_2$ yr^{-1}, mainly due to urban trees), a category not estimated by BMs.

Our results in comparison to other global studies

Figure 10 summarizes our results compared with the main components of the Global Carbon Budget 2021 and with other recent literature. For the Global Carbon Budget 2021 (Friedlingstein et al. 2022), a net land-to-atmosphere sink of -6.0 $GtCO_2$ yr^{-1} is obtained (Figure 10c) when the direct anthropogenic flux from BMs (4.3 $GtCO_2$ yr^{-1} for the period 2001-2020, Figure 10a) is added to the natural terrestrial flux from DGVMs (-10.3 $GtCO_2$ yr^{-1}, Figure 10b). The natural terrestrial sink closely matches the land sink (-10.1 $GtCO_2$ yr^{-1}) estimated as the residual from the other flux components of the global carbon budget (i.e., fossil fuels, atmosphere, and ocean - which are less uncertain than the natural terrestrial sink - and land use change, Friedlingstein et al. 2022). This consistency arising from using two independent approaches provides confidence on the estimated size of the net global land sink

-Figure 10-

Consistent with Friedlingstein et al. (2022), the adjusted BM results obtained in our study (Figure 10d, i.e. Figure 10a plus the striped managed forest area in Figure 10b) compare well with the NGHGIs (Figure 10e), with both datasets indicating a relatively small net sink in managed land globally. This sink results from a large net sink in temperate and boreal regions (mostly represented by AI countries) and a small net source in the tropics (mostly represented by NAI countries, Figure 7a). However, a few lines of reasoning and evidence suggest a possible underestimation of the net global sink in managed land, in both the adjusted BM results and the NGHGIs.

First, the fact that 80% of land is under some form of management (Erb et al. 2017) could suggest, as a first approximation, that a similar share of the total (forest and non-forest) natural terrestrial sink due to indirect effects (Figure 10b) - i.e. about -8 $GtCO_2$ yr^{-1}-, is in managed land. If this hypothetical sink is summed up to the original BM results (about 4 $GtCO_2$ yr^{-1}, Figure 10a), it would result in a net global sink in managed land of approximately -4 $GtCO_2$ yr^{-1}.

Second, the net global sink in our estimates (both adjusted BM results and NGHGIs) is lower than most of the recent literature. For instance, Deng et al. (2022) – an inverse modelling study corrected for CO_2 emissions induced by lateral fluxes to produce terrestrial carbon stock changes estimates that can be compared to our study – estimated a sink of -5.1 $GtCO_2$ yr^{-1} in all land for the period 2007-2017, mostly from managed lands (Figure 10f). Deng et al. (2022) also pointed out to larger sinks over managed lands than the NGHGIs in Russia, EU and Canada, suggesting that some carbon storage processes may be underestimated in NGHGIs, such as the carbon increase in trees outside forests (urban green areas, trees on grassland and cropland, arctic shrubs) and in soils. Harris et al. (2021), integrating remote sensing data with a map of biomass complemented by forest growth curves, harvest and fires removals, estimated a net global forest sink of -7.6 $GtCO_2$ yr^{-1} for the period 2000-2019, mostly occurring on non-primary (or non-intact) forests of temperate and boreal regions. For the same period, Xu et al. (2021), based on annual biomass maps obtained with optical and LiDAR data and a machine learning model, estimated a net global sink of -0.8 $GtCO_2$ yr^{-1} (-3.2 $GtCO_2$ yr^{-1} including adjustments for intact forest gain) for aboveground biomass only. Similarly, Yang et al. (in prep.), using a global L-Band vegetation optical depth (data from https://carbonstocks.kayrros.com), inferred a net global sink in above-ground biomass of -1.9 $GtCO_2$ yr^{-1}, mostly in extra-tropical regions. It should be noted that the latter two studies do not include below ground biomass and non-biomass carbon pools (such as soils), and thus likely underestimate the global net sink.

Third, the sink due to both direct effects (estimated by BMs) and indirect effects in managed forest (i.e. our adjustment to BMs, estimated by DGVMs) might be underestimated. BMs have a relatively simple representation of the management of forests and other land uses, e.g. they include harvest but not other practices that typically stimulate higher forest productivity and would thus cause larger sinks (e.g., Kauppi et al. 2020). The DGVMs runs used here (S2, including only indirect and natural effects) do not include a mechanistic description of forest management (i.e. magnitude and frequency of harvesting operation, stocking density), and forest demography (age-class structure, Pugh et al. 2019) in general, and therefore cannot predict the impact of changes in management and age dynamics on the intensity of indirect effects. As a result, our adjustment method assumes that the sink per unit area due to indirect effects is identical in managed and unmanaged forests (or in young and old forests) under the same climate conditions. Although rising CO_2 stimulates photosynthesis, the overall impact on the net carbon sink is complex (taking resource limitations, respiratory losses, and other factors into account) and is an active area of research (Walker et al., 2020). There is some evidence suggesting that the effect of rising CO_2 on the net sink could be larger in managed or young than in pristine or mature ecosystems (Walker et al. 2019, Jiang et al., 2020, Gundersen et al. 2021). Given the limitations of the DGVM

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ensemble in modelling forest successional stages, this reasoning implies that the sink in managed forests would be larger than the model ensemble estimate (in Figure 10b the dashed green area should be bigger and the dark green area smaller).

Fourth, while the total natural terrestrial sink in Figure 10b includes a large sink from non-forest areas, the latter sink implicitly includes the 'loss of additional sink capacity' (see above) and therefore is likely overestimated. Consequently, a corresponding underestimation of the natural sink in forest areas is implied (i.e., the sum of dashed and dark green areas in Figure 10b should be bigger and the gray area be smaller) to maintain consistency between the natural terrestrial sink derived from DGVMs and the natural terrestrial sink derived as residual sink, which is constrained by the other budget components from the Global Carbon Budget (Friedlingstein et al. 2022).

Lastly, it is possible that NGHGIs underestimate the overall net sink in managed lands. While a few NGHGIs likely underestimate emissions or overestimate removals of CO_2, these effects are at least partly counterbalanced by the incomplete reporting in terms of land uses (including about 0.3 Billion ha of forest with no estimates of carbon flux, and very scarce data for non-forest land in developing countries, Grassi et al. 2022b) and carbon pools (especially for soil). On top of this, the fact that NGHGIs do not always fully include the impact of human-induced environmental change might suggest an overall underestimation of the net global sink in managed land.

Way forward: how to operationalize comparisons between global models and NGHGIs?

This study focused on the main conceptual difference between BMs and NGHGIs. Our approach reconciles most of the current large gap in land use CO_2 fluxes between the two datasets, and provides a greater level of spatial and process details than previous analyses.

Our adjustment of BM results should be seen as a short-term and pragmatic fix based on existing data, rather than a definitive solution to bridge the difference between global models and NGHGIs. Additional steps are needed - from both global models and NGHGIs - to understand and reconcile the remaining differences, some of which are relevant at the country level, and to operationalize future comparisons between global models and NGHGIs.

From the global models' side, other studies have already highlighted many fundamental challenges (Pongratz et al 2021), including the need for a better representation of land management processes and forest demography. Here we highlight the need for more disaggregated results. For BMs, a greater disaggregation would allow to re-combine results into categories more easily comparable to NGHGIs. For instance, recent studies (e.g., Friedlingstein et al. 2022, Gasser et al. 2022) disaggregated land-use fluxes into gross sources (including deforestation, shifting cultivation, and forest harvest) and gross sinks (including sinks from afforestation, conversion of other land to forest, and forest regrowth after harvest). While distinguishing between gross and

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net deforestation is crucial to assess the impact of policy pledges (Gasser et al. 2022), lumping all fluxes in these two categories (gross sources and gross sinks) does not allow a direct comparison with NGHGIs. This is because, on the one hand, NGHGIs typically report estimates of gross deforestation (i.e. not including forest area expansion), and on the other hand, forest land (including forest expansion) includes both the emissions from forest harvest and the sink from the subsequent regrowth. In this regard, the land use categories used here may offer a blueprint for future studies (including the Global Carbon Budget) because they represent a minimum common denominator between the information provided by most NGHGIs - being aware of the large difference in the quality of reporting between developed and developing countries - and the typical outputs produced by BMs. The proposed different aggregation in models' outputs could open the path to an operational assessment of the collective countries' progress avoiding double accounting parts of the natural land sink.

From a countries' perspective, NGHGIs could be made more comparable to global models if they either restrict their estimates to direct anthropogenic fluxes only (like BMs) or if they broaden their scope to the entire national territory (without distinction between managed and unmanaged lands). The first option is unlikely to be widely applied because most NGHGIs are fully or partly based on direct observations (for example, national forest inventories), which cannot separate the direct human-induced effects from indirect and natural effects. The second option might be feasible but would have relevant implications. On the one hand, countries would be encouraged to invest in the monitoring of areas for which limited information exists, and in protecting the carbon stocks therein: accounting would incentivise measurement and preservation. For example, in countries like Canada and Russia, fires on remote, unmanaged forest land are not suppressed as actively as on managed land, unless there is a direct threat to people or infrastructure. On the other hand, extending the area for which CO_2 fluxes are reported and accounted for in the NGHGIs would imply large (and potentially uncontrollable) compliance risks to the country (e.g., permafrost thawing). Already now, following IPCC methodologies (IPCC 2019), countries like Canada and Australia exclude emissions from large natural disturbances, and the subsequent CO_2 removals on the same area (with the assumption that fluxes compensate over time), with the aim to isolate better the anthropogenic signal on land-use emissions, and to reduce the risk that uncontrollable events hamper the fulfilment of the country's climate targets (IPCC 2019, Kurz et al. 2018). Due to this compliance risk, the second option is not realistically applicable to all countries. However, quantification of GHG emissions and removals on unmanaged land remains of high scientific and policy relevance and should be encouraged. In this context, any possible broadening of the scope beyond anthropogenic fluxes brings with it the risk of double-counting of carbon fluxes compared to global models. Climate policies are usually based on mitigation pathways derived by IAMs, which follow the BM's definition of land-use fluxes (Grassi et al. 2021). Including fluxes attributed to the natural terrestrial sink to a broader territorial scope requires adjustment of the mitigation pathways or policy targets to avoid double-counting of sinks.

A more realistic way forward for countries is to continue with the current approach, based on the managed land proxy specified at the country level, while investing in a number of key improvements. First, NGHGIs need to provide more transparent and traceable information on all their managed land (i.e., forest and non-forested

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areas), including maps and information on the extent to which indirect and natural effects are included. This will enable the scientific community to provide an independent (yet comparable) assessment of the NGHGI estimates, thus increasing trust in land-use flux estimates. This aspect is especially crucial in developing countries, where the lack of specific information on managed and unmanaged areas is one of the largest knowledge gaps in the LULUCF part of most NGHGIs. In this regard, important improvements towards a more transparent and harmonized reporting are expected under the Paris Agreement's Transparency Framework (https://unfccc.int/enhanced-transparency-framework), starting at the end of 2024. Second, countries need to improve the accuracy and completeness of their NGHGIs. Many NGHGIs are still incomplete, especially for soil carbon and non-forest land categories, where observation-based estimates are often lacking. In this regard, a huge effort in capacity building for estimating land-use fluxes is needed in those developing countries with limited resources and experience in reporting, based on existing efforts and lessons learned (e.g., in the context of REDD+). This effort could involve the scientific community, e.g. in making products from Earth Observation and/or modelling directly usable by GHG inventory experts for building maps of GHG fluxes, in combination with the direct observations and statistics already available in the country. Third, the voluntary inclusion of information on non-anthropogenic fluxes from unmanaged lands in national reporting, although not used for accounting purposes, would help to better understand the responses of terrestrial ecosystems to climate change; this information could include processes in unmanaged land (for example, fires, permafrost thawing) that are relevant for assessing progress towards the goals of the Paris Agreement (Grassi et al. 2018, IPCC 2019).

Overall, in the short-to-medium term, it is unlikely that countries will change their approach to reporting only anthropogenic land-use fluxes, as historical consistency is a crucial aspect in reporting and policy planning. However, having more transparent, accurate, and complete NGHGIs would be already a major achievement. As many NAI countries are in the middle of developing more sophisticated monitoring systems to comply with Paris Agreement requirements, improvements can be expected in the upcoming years. Improving NGHGIs data is also critical for countries to track the impacts of land-related climate policies at national level and for updating successive NDCs. Significant progress in reducing the gap between global models and NGHGIs can also be made by a different aggregation of models' results, as shown in our study. This is an easier task than changing the approach in the countries' NGHGI systems that are based on established IPCC guidelines and UNFCCC reporting decisions. The aggregation, upscaling and reconciliation of NGHGIs with the Global Carbon Budget provides an iterative process to improve carbon accounting systems and support the global stocktake towards the Paris Agreement targets.

Conclusions

This study confirms a substantial gap in land-use flux estimates between BMs and NGHGIs, equal to 6.0 $GtCO_2$ yr^{-1} globally for the period 2001-2020 and mostly occurring on forest land. For the first time, we also provide a

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comprehensive comparison for specific categories, such as deforestation, organic soil, and agricultural land. When BMs, reflecting direct anthropogenic effects only, are adjusted with estimates from DGVMs to incorporate the human-induced environmental change (indirect human-induced effects) on managed forests, the gap is strongly reduced at the global level (i.e., 0.9 $GtCO_2$ yr^{-1}) and for most regions and countries. This confirms that most of the difference in land CO_2 fluxes between global models and countries is not due to a difference in the estimated fluxes in a given area, but rather due to whether these fluxes are considered anthropogenic or natural, and whether they are accounted for under the Paris Agreement. Considering fluxes anthropogenic or natural in NGHGIs is most often an unintended product of the accounting methodologies used. By making estimates of BMs conceptually and quantitatively more comparable to NGHGIs, our approach contributes to bridging these two different communities and enables methodological improvements and consistency with global budgets that determine climate trajectories and pathways to net-zero emissions.

Some relevant discrepancies remain, especially in developing countries, which deserve further investigation from both the NGHGIs and the global models' sides. For example, the adjusted BMs' results provide a forest sink that is often greater than NGHGIs, especially in Latin America; in Asia, BMs estimate higher CO_2 emissions from deforestation and agricultural lands than NGHGIs; in Africa, BMs estimate smaller CO_2 emissions from deforestation and higher emissions for agricultural lands than NGHGIs.

Overall, this study provides evidence that the area of managed land, following the broad definition applied in NGHGIs, is very likely a net sink of CO_2 globally. It is possible that this net sink is actually greater than the one derived either from NGHGIs or estimated in this study by combining results from BMs and DGVMs. This is because NGHGIs are often not complete in terms of land uses (especially for non-forest land) and carbon pools (especially for soil), and do not always include the impact of human-induced environmental change. Furthermore, because of the relatively simple representation of management by BMs (i.e., direct human-induced effects), and the lack of consideration of the impact of forest age dynamics on the intensity of CO_2 fertilization by DGVMs (i.e. direct human-induced effects), the sink in our adjusted BM results may be underestimated.

Irrespective of the attribution of the net CO_2 flux in managed land to anthropogenic or natural drivers - which might have implications for countries' climate targets -, it is paramount for climate policy development to understand with greater confidence where this flux occurs (i.e., which country, which land use, which pools are affected), along with its temporal evolution.

By reconciling most of the current differences between global models and NGHGIs, we offer a blueprint for operationalizing future comparisons and simultaneously identifying areas to be further investigated. This study represents a step forward for increasing confidence in LULUCF fluxes reported by countries while building an upscaling framework that ensures greater consistency between country-level efforts and reporting, and the global carbon budget estimated by models. This consistency is crucial to building the necessary confidence in our monitoring and reporting systems to support investment in land-use mitigation and assess countries' collective progress under the Global Stocktake process towards the goals of the Paris Agreement.

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Data availability

The main data from this study are openly available via the Zenodo portal (Grassi et al. 2022a) https://zenodo.org/record/6840951#.YtGbNuxBzFw

Author contribution

G.G. led the study design, performed the analysis and wrote the first draft with the help of J.P., C.S., T.G., R.S.H., S.S., J.G.C., A.C., P.C., S.F., W.K., M.J.S.S. The analysis of DGVM data on non-intact forest was performed by R.A., supported by G.C.; S.F., S.R., R.A.V. and A.K. helped in the analysis of country GHG inventories. J.P., C.S., T.G. and R.S.H. provided data from BMs; S.S., P.F., E.K., D.K., J.K., M.M., J.N., B.P., A.P.W., W.Y., and X.J. provided data from DGVMs. All the authors provided feedback to the manuscript.

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 or any other institution.

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TABLES

Table 1. Categories of land CO_2 fluxes from NGHGIs and bookkeeping models analysed in this study.

	NGHGIs (see Grassi et al. 2022b for details)	**Bookkeeping models** (see Friedlingstein et al. 2022 for details)		
		H&N	**BLUE**	**OSCAR**
Managed Forest land	Fluxes in existing forest (including 'forest land remaining forest land', 'land converted to forest', and carbon stock changes in harvested wood products, but excluding organic soils)	Fluxes from industrial and fuel wood harvest and subsequent regrowth, product decay, plantation, recovery of forest after shifting cultivation, conversion of any type of land to forest, and fire suppression	Fluxes from wood harvest and subsequent regrowth, product decay, recovery of forest after shifting cultivation, conversion of any type of land to forest	Fluxes from wood harvest and subsequent regrowth, product decay, conversion of any type of land to forest (including recovery of forest after shifting cultivation)
Deforestation	Fluxes due to area converted from forest to other land use categories in the last 20 years, excluding fluxes from organic soils.	Fluxes due to conversion of forested land to croplands/ pastures/other lands	Fluxes due to conversion of forested land to croplands/ pastures (including emissions due to shifting cultivation)	Fluxes due to conversion of forested land to any other type of land (including due to shifting cultivation)
Organic soils	Fluxes from organic soils in various land categories (forest land, cropland, grassland)	Fluxes on peatland from external dataset	Fluxes on peatland from external dataset	Fluxes on peatland from external dataset (same as BLUE)
Other managed land	Fluxes from lands not included in the above categories (e.g. cropland, grassland, wetland, settlements,and conversion non involving forests)	Fluxes due to changes in non-forest land (conversions between croplands, pastures and other lands)	Fluxes due to changes in non-forest land (conversions between croplands and pastures, clearing and regrowth of non-forest ecosystems, changes in croplands/pastures/harvesting)	Fluxes due to harvest in non-forested land, all other conversions (between non-forested natural lands, croplands, pastures, urban lands)
LULUCF net	Sum of fluxes of the categories above, as reported in the Common Reporting Format tables	Sum of fluxes of the categories above ('ELUC net')	Sum of fluxes of the categories above ('ELUC net')	Sum of fluxes of the categories above ('ELUC net')

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FIGURE CAPTIONS

Figure 1. Conceptual illustration of the different approaches for estimating the anthropogenic and natural land CO_2 fluxes by global models used in the Global Carbon Budget (bookkeeping models and Dynamic Global Vegetation Models, DGVMs) and by countries' National GHG inventories (NGHGIs). Bookkeeping models consider as anthropogenic only the fluxes that are due to direct human-induced effects, such as land-use change, shifting cultivation, harvest, and regrowth. By contrast, countries in their NGHGIs generally consider as anthropogenic all the fluxes occurring on a larger area of managed forest than the one used by models, and include most of indirect human-induced effects on this area that models consider natural (i.e. the natural response to human-induced environmental changes such as increased CO_2 atmospheric concentration and nitrogen deposition, which enhance tree growth). NGHGIs do not consider fluxes from unmanaged lands. Note that the figure is an oversimplification: DGVMs can also estimate the anthropogenic flux, but here only the natural fluxes are shown (see Methods); not all NGHGIs include all indirect effects in managed land; other differences between BMs and NGHGIs exist that are not included in this figure, e.g. on the representation of forest management and forest demography.

Figure 2. (a) Forest map used in this study, based on maps of intact forest (Potapov et al., 2017) and non-intact forest (total forest area from Hansen et al., 2013 minus intact forest area), except for Canada and Brazil where the NGHGI maps of managed and unmanaged forest are used (see Supplementary Information); (b-g) statistics of managed and unmanaged forest in 2015 based on NGHGIs (Grassi et al. 2022b) compared to the forest map used in this study, for the world and five macro-regions (see Supplementary Table1 for individual countries). This study uses the maps of intact and non-intact forests as a proxy for unmanaged and managed forests, respectively, except for Brazil and Canada where the country maps of unmanaged and managed forests were available.

Figure 3. CO_2 fluxes from LULUCF between 2001 and 2020 (panel a), forest land (b, including harvested wood products and excluding organic soils), deforestation (c), organic soils (d), and other fluxes (e, including cropland and grassland), from bookkeeping models (BMs) and National GHG inventories (NGHGIs). The values of BMs are those used in the Global Carbon Budget 2021 (Friedlingstein et al., 2022); values for NGHGIs are from Grassi et al. (2022). For organic soils, BLUE and OSCAR use the same external dataset, and their lines thus lie on top of each other.

Figure 4. Global land-use CO_2 fluxes from recent studies: BMs in the Global Carbon Budget 2020 (Friedlingstein et al., 2021) and in the IPCC 6th Assessment Report (IPCC, 2022a); Integrated Assessment Models (IAMs) and NGHGIs in (Grassi et al., 2021); BMs in the Global Carbon Budget 2021 Friedlingstein et al. (2022) and NGHGIs in Grassi et al. (2022). On the right, the gaps between global models and NGHGIs estimated by Grassi et al. (2021) (for the period 2005-2015) and by this study (for 2001-2020) are shown.

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Figure 5. CO_2 fluxes due to environmental change (indirect human-induced effects) for intact and non-intact forests from 2001 to 2020 (panel a, average of 17 DGVMs), and for non-intact forest only (b, average, and values of individual DGVMs). The DGVM simulations used here are the ones performed for the Global Carbon Budget 2021 (Friedlingstein et al. 2022).

Figure 6. Adjusted CO_2 fluxes from BMs for LULUCF (panel a) and for forest land (b), i.e. original BM results plus the natural sink from DGVMs in non-intact forest, compared to the NGHGIs for the period 2001-2020.

Figure 7. LULUCF CO_2 fluxes (average 2001-2020) from BMs, from the sum of BMs and DGVMs (in the non-intact forest only) and from NGHGIs, for the world, Annex I countries (AI) and Non Annex I countries (NAI, panel a), for five macro-regions (b) and for 10 large individual countries (c).

Figure 8. Land CO_2 fluxes (average 2001-2020) from BMs, from the sum of BM and DGVMs (in non-intact forest only) and from NGHGIs for the total LULUCF sector, forest land (including harvested wood products and excluding organic soils), deforestation, organic soils, and other (cropland, grassland, etc.) at world level (panel a), for Annex I countries (b), and for Non Annex I countries (c).

Figure 9. Land CO_2 fluxes (average 2001-2020) from BMs, from the sum of BMs and DGVMs (in non-intact forest only) and from NGHGIs for forest land (panels a and b, including harvested wood products and excluding organic soils), deforestation (c and d), organic soils (e and f), and other (g and h, including cropland, grassland, etc). A larger number of country-level data are included in Supplementary Table 1.

Figure 10. Components of the global land CO_2 flux from various sources: (a) flux due to direct anthropogenic effects from BMs; (b) natural terrestrial sink, reflecting the indirect anthropogenic effects on managed forest (striped area), on unmanaged forest (green area) and on non-forest land (grey area) as decomposed in our study; (c) net land-to-atmosphere flux (sum of (a) and total area in (b)); (d) adjusted BMs results ((a) + striped area in (b)); (e) net flux on managed land from NGHGIs (Grassi et al., 2022); (f) results from inversion models for managed (dashed area) and unmanaged lands (Deng et al., 2022). Estimates in columns a, b and c are from Friedlingstein et al. (2022) and refer to averages for the period 2001-2020 (like columns d and e). Estimates in column f refer to the period 2007-2017.

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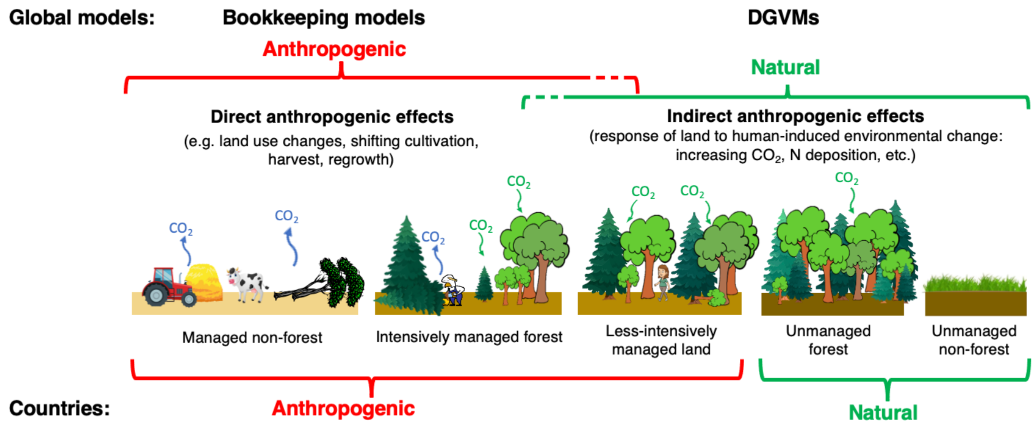
FIGURES



930 **Figure 1**. Conceptual illustration of the different approaches for estimating the anthropogenic and natural land CO_2 fluxes by global models used in the Global Carbon Budget (bookkeeping models and Dynamic Global Vegetation Models, DGVMs) and by countries' National GHG inventories (NGHGIs). Bookkeeping models consider as anthropogenic only the fluxes that are due to direct human-induced effects, such as land-use change, shifting cultivation, harvest, and regrowth. By contrast, countries in their NGHGIs generally consider as anthropogenic all the fluxes occurring on a larger area of managed forest than the one used by models, and include most of indirect human-induced effects on this area that models consider natural (i.e. the natural response to human-induced environmental changes such as increased CO_2 atmospheric concentration and nitrogen deposition, which enhance tree growth). NGHGIs do not consider fluxes from unmanaged lands. Note that the figure is an oversimplification: DGVMs can also estimate the anthropogenic flux, but here only the natural fluxes are shown (see Methods); not all NGHGIs include all indirect effects in managed land; other differences between BMs and NGHGIs exist that are not included in this figure, e.g. on the representation of forest management and forest demography.

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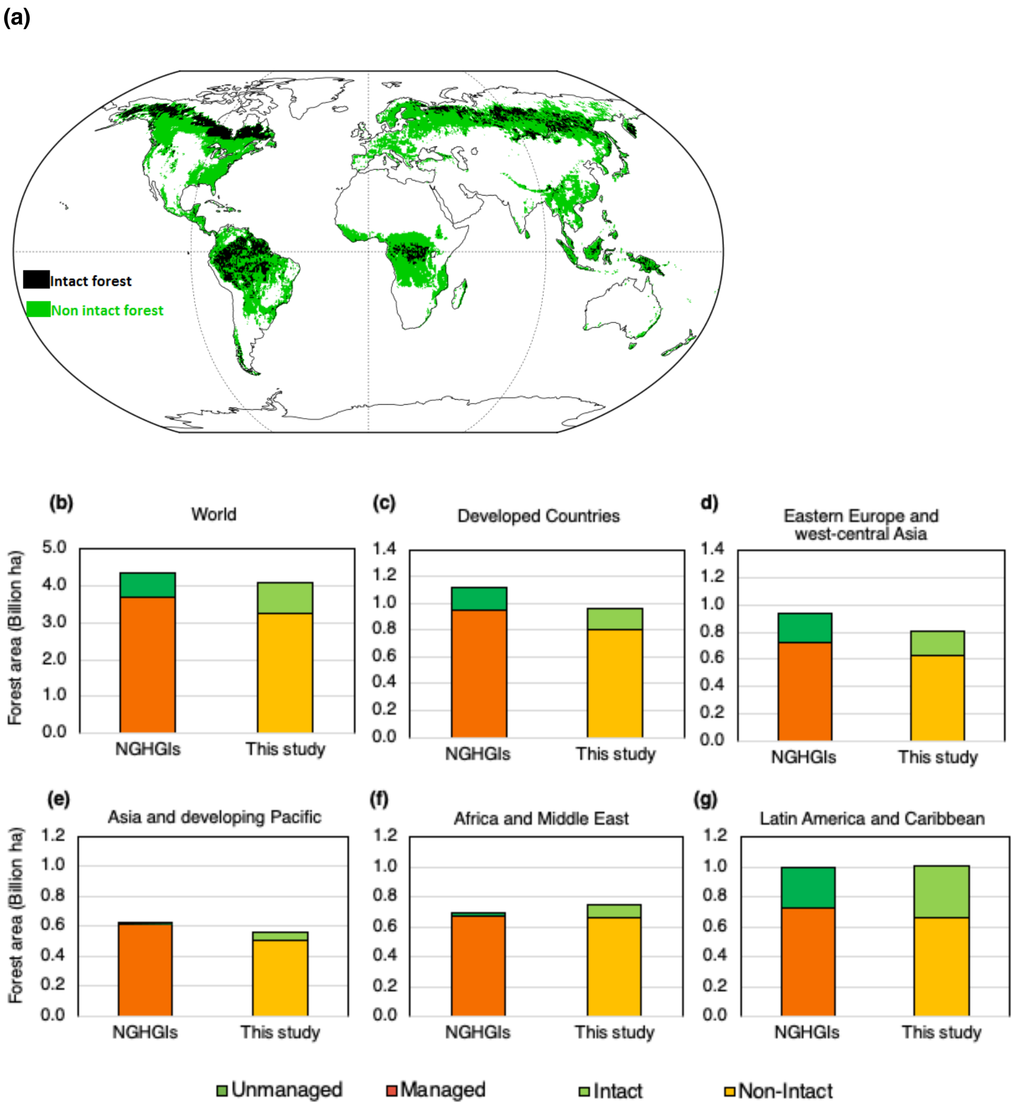

Figure 2. (a) Forest map used in this study, based on maps of intact forest (Potapov et al., 2017) and non-intact forest (total forest area from Hansen et al., 2013 minus intact forest area), except for Canada and Brazil where the NGHGI maps of managed and unmanaged forest are used (see Supplementary Information); (b-g) statistics of managed and unmanaged forest in 2015 based on NGHGIs (Grassi et al. 2022b) compared to the forest map used in this study, for the world and five macro-regions (see Supplementary Table1 for individual countries). This study uses the maps of intact and non-intact forests as a proxy for unmanaged and managed forests, respectively, except for Brazil and Canada where the country maps of unmanaged and managed forests were available.

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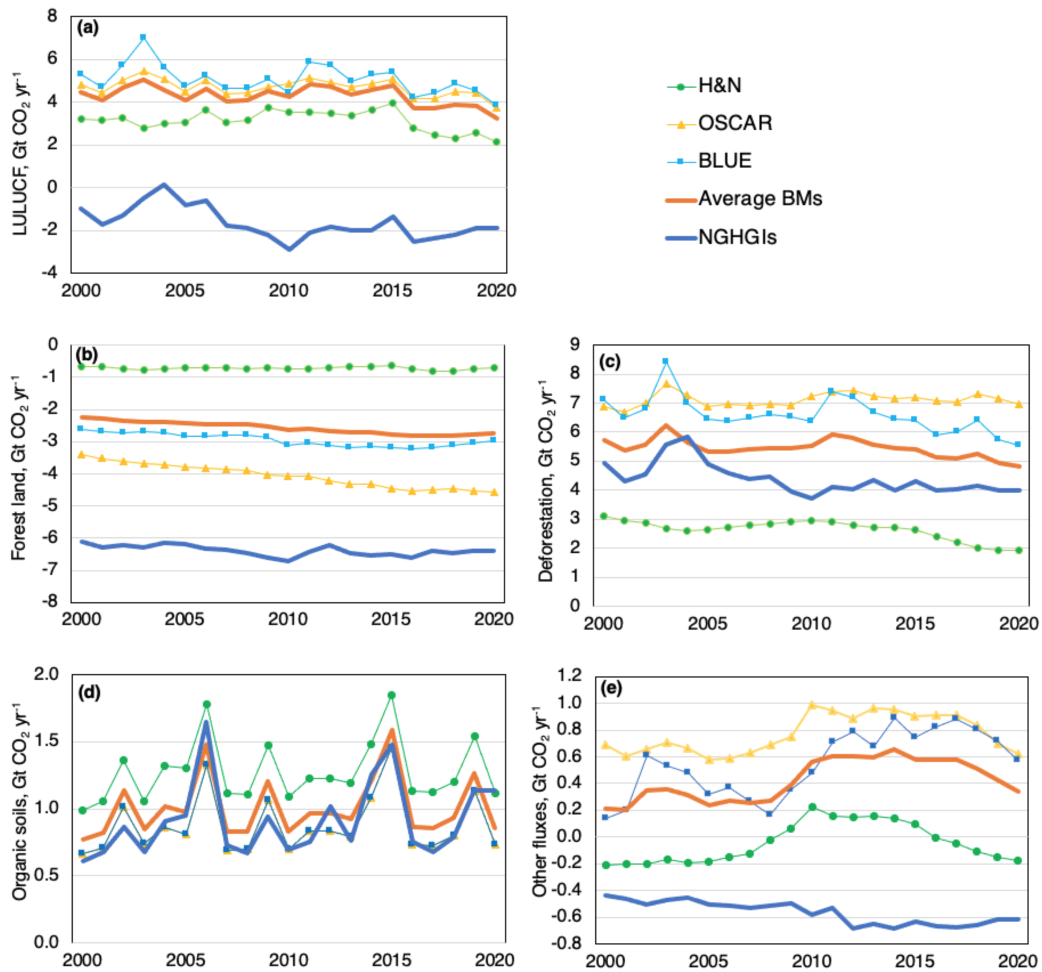

Figure 3. CO_2 fluxes from LULUCF between 2001 and 2020 (panel a), forest land (b, including harvested wood products and excluding organic soils), deforestation (c), organic soils (d), and other fluxes (e, including cropland and grassland), from bookkeeping models (BMs) and National GHG inventories (NGHGIs). The values of BMs are those used in the Global Carbon Budget 2021 (Friedlingstein et al., 2022); values for NGHGIs are from Grassi et al. (2022). For organic soils, BLUE and OSCAR use the same external dataset, and their lines thus lie on top of each other.

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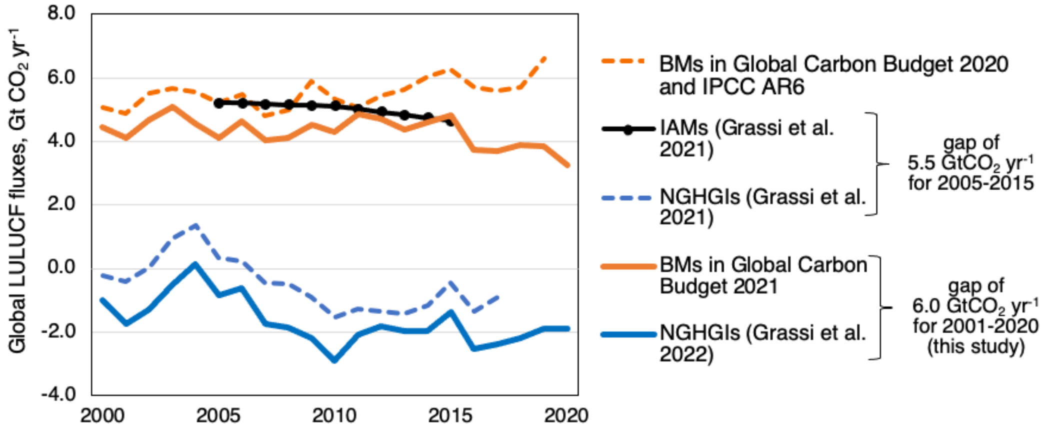

965 **Figure 4**. Global land-use CO_2 fluxes from recent studies: BMs in the Global Carbon Budget 2020 (Friedlingstein et al., 2021) and in the IPCC 6th Assessment Report (IPCC, 2022a); Integrated Assessment Models (IAMs) and NGHGIs in (Grassi et al., 2021); BMs in the Global Carbon Budget 2021 Friedlingstein et al. (2022) and NGHGIs in Grassi et al. (2022). On the right, the gaps between global models and NGHGIs estimated by Grassi et al. (2021) (for the period 2005-2015) and by this study (for 2001-2020) are shown.

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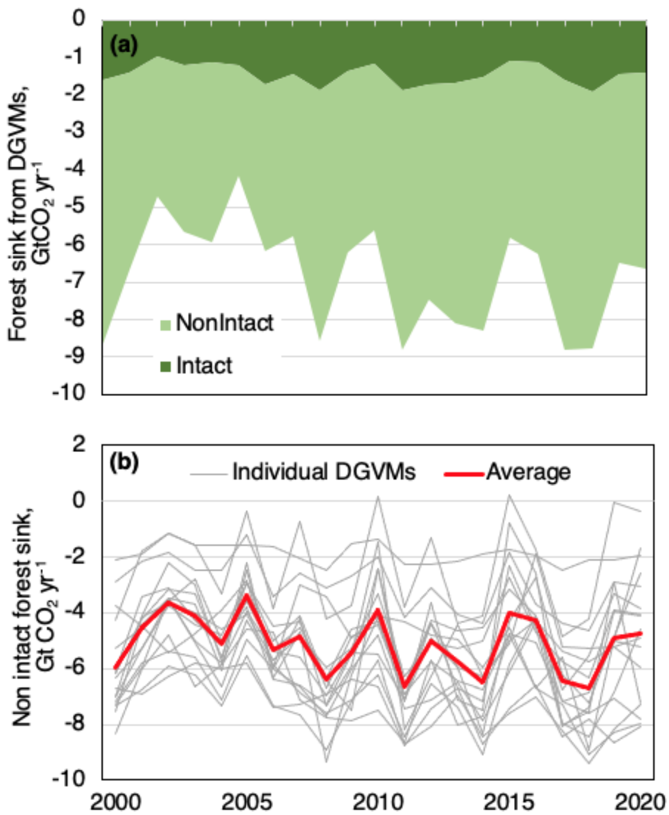

Figure 5. CO_2 fluxes due to environmental change (indirect human-induced effects) for intact and non-intact forests from 2001 to 2020 (panel a, average of 17 DGVMs), and for non-intact forest only (b, average, and values of individual DGVMs). The DGVM simulations used here are the ones performed for the Global Carbon Budget 2021 (Friedlingstein et al. 2022).

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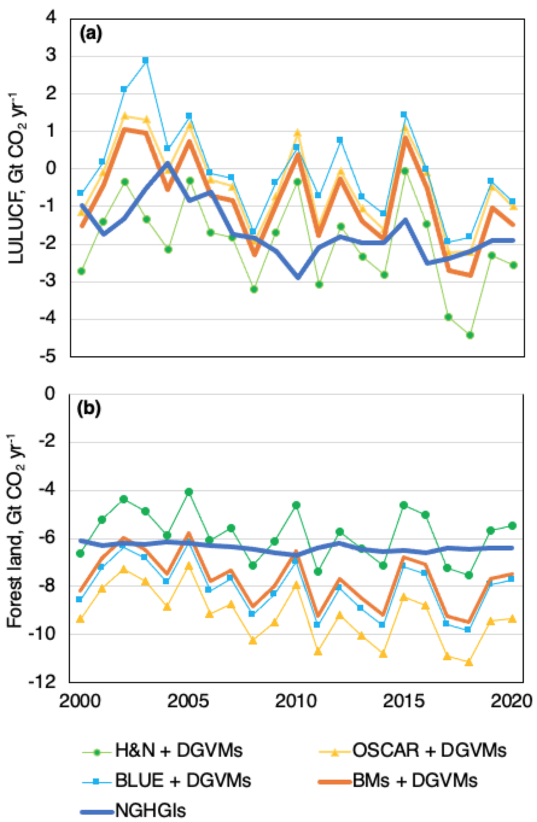

Figure 6. Adjusted CO_2 fluxes from BMs for LULUCF (panel a) and for forest land (b), i.e. original BM results plus the natural sink from DGVMs in non-intact forest, compared to the NGHGIs for the period 2001-2020.

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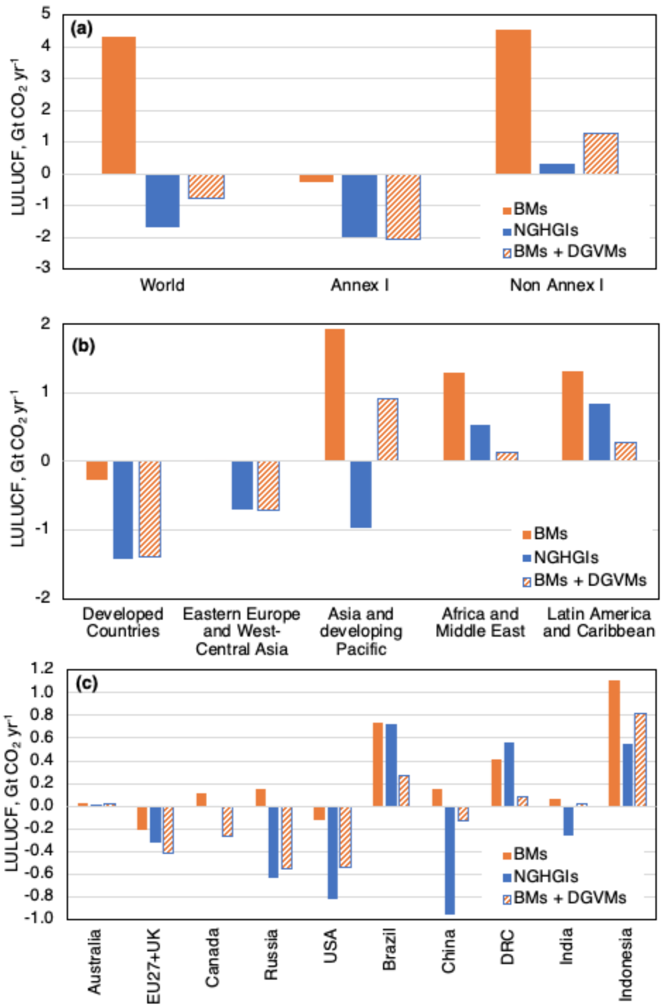

Figure 7. LULUCF CO_2 fluxes (average 2001-2020) from BMs, from the sum of BMs and DGVMs (in the non-intact forest only) and from NGHGIs, for the world, Annex I countries (AI) and Non Annex I countries (NAI, panel a), for five macro-regions (b) and for 10 large individual countries (c).

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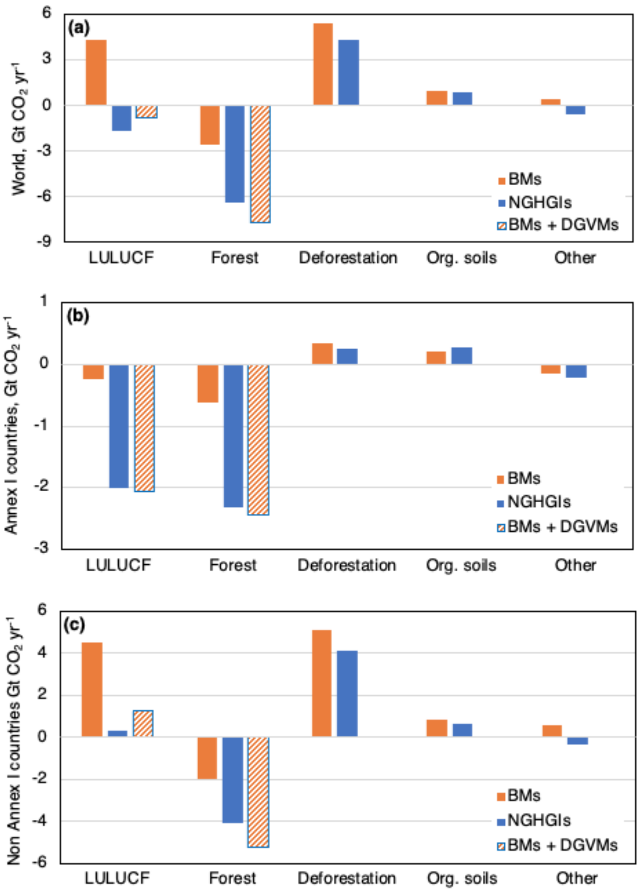

Figure 8. Land CO_2 fluxes (average 2001-2020) from BMs, from the sum of BM and DGVMs (in non-intact forest only) and from NGHGIs for the total LULUCF sector, forest land (including harvested wood products and excluding organic soils), deforestation, organic soils, and other (cropland, grassland, etc.) at world level
990 (panel a), for Annex I countries (b), and for Non Annex I countries (c).

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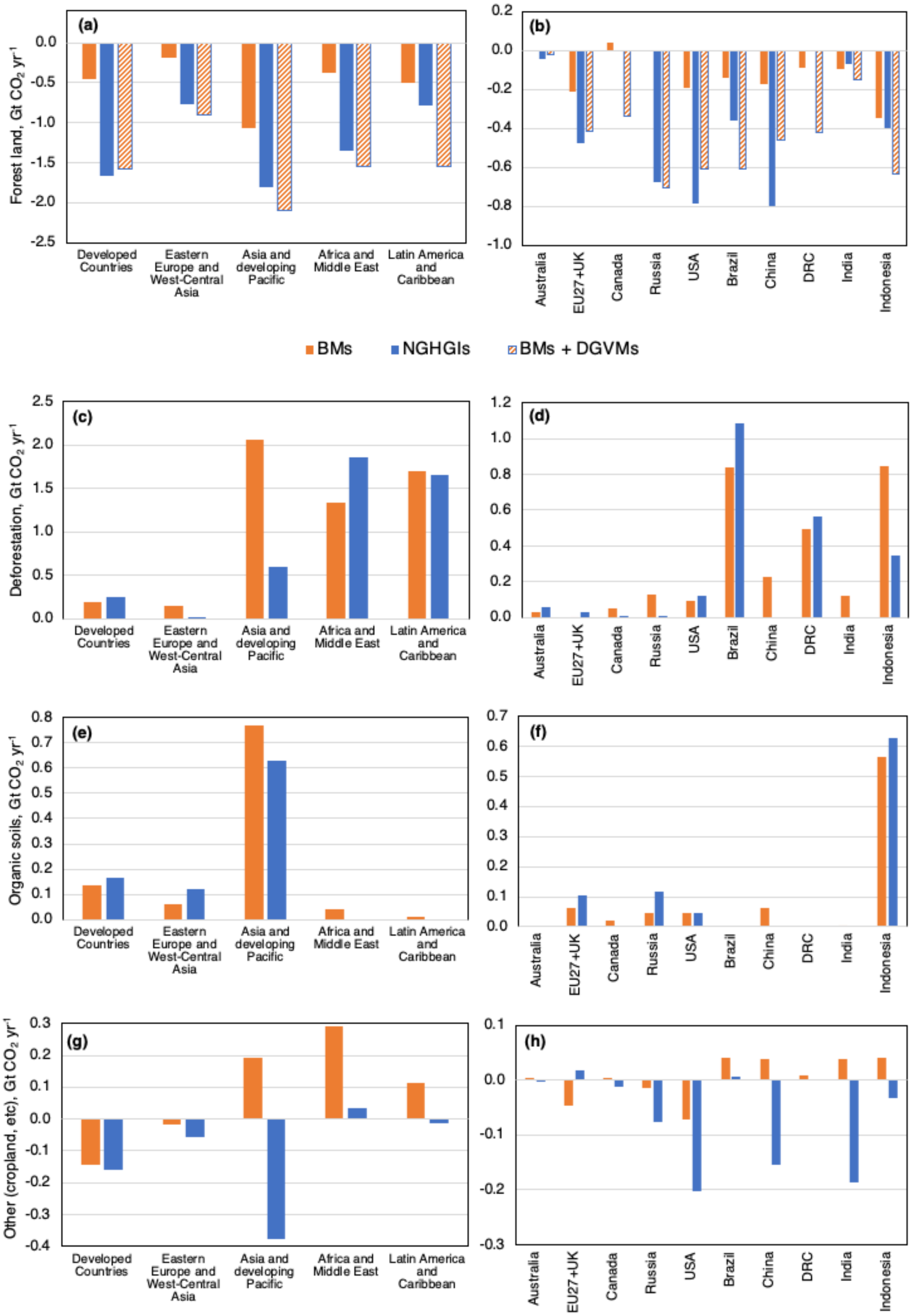

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Figure 9. Land CO_2 fluxes (average 2001-2020) from BMs, from the sum of BMs and DGVMs (in non-intact forest only) and from NGHGIs for forest land (panels a and b, including harvested wood products and excluding organic soils), deforestation (c and d), organic soils (e and f), and other (g and h, including cropland, grassland, etc). A larger number of country-level data are included in Supplementary Table 1.

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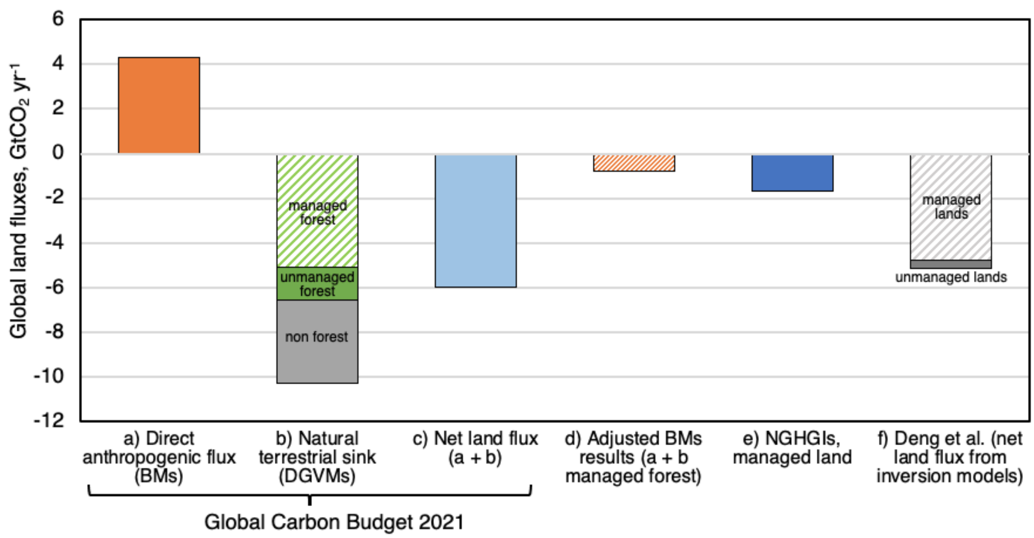

Figure 10. Components of the global land CO_2 flux from various sources: (a) flux due to direct anthropogenic effects from BMs; (b) natural terrestrial sink, reflecting the indirect anthropogenic effects on managed forest (striped area), on unmanaged forest (green area) and on non-forest land (grey area) as decomposed in our study; (c) net land-to-atmosphere flux (sum of (a) and total area in (b)); (d) adjusted BMs results ((a) + striped area in (b)); (e) net flux on managed land from NGHGIs (Grassi et al., 2022); (f) results from inversion models for managed (dashed area) and unmanaged lands (Deng et al., 2022). Estimates in columns a, b and c are from Friedlingstein et al. (2022) and refer to averages for the period 2001-2020 (like columns d and e). Estimates in column f refer to the period 2007-2017.