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Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks

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Achieving the long-term temperature goal of the Paris Agreement requires forest-based mitigation. Collective progress towards this goal will be assessed by the Paris Agreement's Global stocktake. At present, there is a discrepancy of about 4 $GtCO_2\,yr^{-1}$ in global anthropogenic net land-use emissions between global models (reflected in IPCC assessment reports) and aggregated national GHG inventories (under the UNFCCC). We show that a substantial part of this discrepancy (about 3.2 $GtCO_2\,yr^{-1}$) can be explained by conceptual differences in anthropogenic forest sink estimation, related to the representation of environmental change impacts and the areas considered as managed. For a more credible tracking of collective progress under the Global stocktake, these conceptual differences between models and inventories need to be reconciled. We implement a new method of disaggregation of global land model results that allows greater comparability with GHG inventories. This provides a deeper understanding of model–inventory differences, allowing more transparent analysis of forest-based mitigation and facilitating a more accurate Global stocktake.

The long-term goals of the Paris Agreement include holding "the increase in the global average temperature to well below 2 °C" (Article 2) and require achieving globally "…a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century …" (Article 4)[1]. It is generally understood that 'anthropogenic' applies to both emissions and removals[2]. Reaching this balance requires a simultaneous dramatic reduction of fossil-fuel and land-based GHG emissions, while also creating net CO_2 sinks (negative emissions)[3], especially in forests[4–6].

The Paris Agreement includes a 'Framework for transparency of actions', to track the progress of countries towards achieving their individual targets (that is, the Nationally Determined Contributions, NDCs), and a periodic 'Global stocktake, to assess the countries' collective progress towards the long-term goals of the Paris Agreement "in the light of ... the best available science" (Article 14). The Global stocktake is potentially the engine of the Paris Agreement, because any identified emission gap between collective progress and the 'well-below 2 °C trajectory' is expected to motivate increased mitigation ambition by countries in successive rounds of NDCs.

The details of the Global stocktake are still to be defined under the UNFCCC. Given the progress in climate negotiations and the close linkage between the UNFCCC and IPCC processes (see Methods), we assume that inputs to the Global stocktake will use scientific estimates of GHG trajectories for the well-below-2 °C trajectory (summarized by the Sixth Assessment Report of the IPCC, AR6) as the benchmark with which the planned collective progress (based on country reports) will be compared to assess the emission gap (Fig. 1a). This approach requires that scientific estimates and country data are comparable and consistent for the historical period (Fig. 1b).

Recent studies[5,7] highlighted a discrepancy of about 3 $GtCO_2\,yr^{-1}$ for the 2000s in global anthropogenic land-related GHG emission estimates, with lower values reported in national GHG inventories (GHGIs) compared with global modelling approaches[8] used in the Fifth Assessment Report of the IPCC (AR5). One suggested reason for this discrepancy is the different approaches used to estimate anthropogenic forest CO_2 removal (that is, the sink)[5]. Updated model[9] and GHGI estimates widen this gap to about 4 $GtCO_2\,yr^{-1}$ for the period 2005–2014 (Fig. 2); that is, 10% of total anthropogenic

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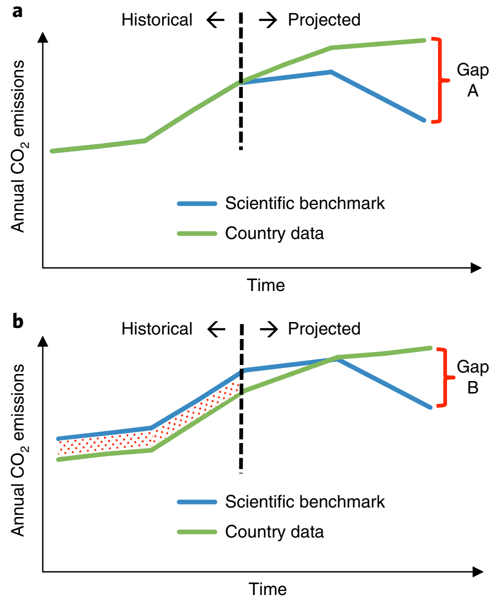

Fig. 1 | Conceptual diagram of the impact of mismatches in anthropogenic land flux estimates on the gap between country pledges and what is required to meet climate targets. The Global stocktake's assessment of collective progress towards the long-term targets of the Paris Agreement will probably benchmark the scientific trajectories of GHG emissions reductions against the projected collective country GHG mitigation targets (NDCs) to identify the expected emission gap[38,50,51] and the need for increased policy ambition. **a**, The ideal situation, in which the scientific benchmark and country data match in the historical period. **b**, Current situation, in which countries report lower emissions (see Fig. 2). This discrepancy (red dotted area in **b**) may lead to an underestimation of the future emission gap, that is gap B is smaller than gap A. Even if these discrepancies are corrected (for example, ref. [37]), the uncertainty of the emission gap may still increase[38].

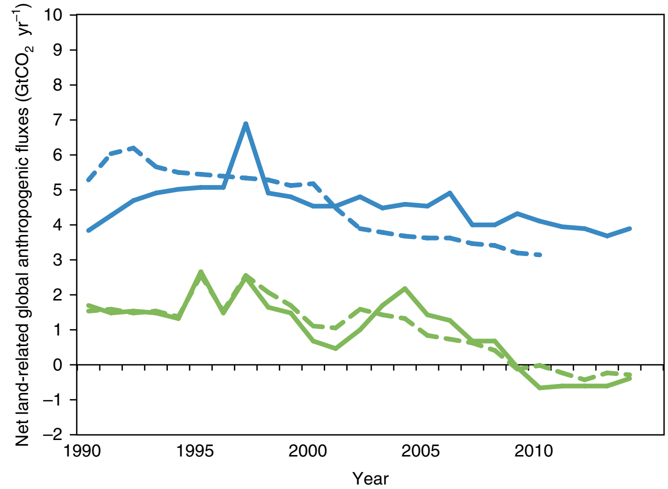

Fig. 2 | Comparison of the global net anthropogenic land-related CO_2 fluxes estimated by AR5 and countries' GHGIs. The flux in AR5 WGI table 6.1[20] and WGIII table 11.1[21] was based on the bookkeeping model from Houghton et al.[8] (dashed blue line), updated in this figure using ref. [9] (solid blue line). This is compared with countries' GHGIs from ref. [5] (dashed green line), updated in this study (solid green line). The gap between the updated estimates is about 4 $GtCO_2$ yr^{-1} for the period 2005–2014. Positive fluxes indicate net emissions, whereas negative fluxes indicate net removals of CO_2 from the atmosphere. See Methods for details.

CO_2 emissions in this period[10]. Understanding and reconciling this discrepancy is essential for the Global stocktake.

The countries' GHGIs (following the IPCC methodological Guidelines[11]) and the global models assessed in the IPCC assessment reports both aim to identify anthropogenic GHG fluxes from land. This is challenging, as land-related fluxes are determined by natural and anthropogenic processes, and are also the most uncertain component of the global carbon budget[10]. Three types of effects can drive land GHG fluxes (see Fig. 3a, building on ref. [12]): (1) direct human-induced effects, including land-use changes and management practices; (2) indirect human-induced effects, such as human-induced environmental changes (for example, temperature, precipitation, CO_2 and nitrogen deposition feedbacks) that affect growth, mortality, 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 country GHGIs) and the IPCC assessment reports have developed different approaches to identify anthropogenic GHG fluxes. Both approaches are valid in their own specific contexts, yet both are also incomplete.

Here we show the main conceptual differences between country GHGIs and global models when estimating the anthropogenic net sink, and propose and evaluate a disaggregation of forest net CO_2 flux estimates by global models to facilitate a comparison with GHGIs. Our main focus is on developed countries, where the analysis is based on detailed and consolidated country data. We also provide estimates for developing countries, which are less robust due to data limitations, to highlight the global relevance of our analysis. Finally, we discuss the implications of our findings in the context of the ongoing IPCC work programme, the country GHG reporting to the UNFCCC and the Global stocktake.

UNFCCC GHGI community

All Parties to the UNFCCC are required to report national GHGIs of anthropogenic emissions and removals, with different obligations for developed and developing countries (Supplementary Section 1). The quality of GHGIs, although it varies between countries, is gradually improving over time[7,13].

Due to the difficulty in providing widely applicable and scientifically robust methods to disentangle direct and indirect human-induced and natural effects on land-based GHG fluxes, the IPCC Guidelines adopted the 'managed land' concept[11] as a pragmatic proxy to facilitate GHGI reporting. Anthropogenic land GHG fluxes (direct and indirect) are defined as all those occurring on managed land, that is, where human interventions and practices have been applied to perform production, ecological or social functions[11] (Supplementary Section 1). The contribution of natural effects on managed lands is assumed to be negligible over time[12]. GHG fluxes from unmanaged land are not reported in GHGIs[14] because they are assumed to be non-anthropogenic.

The specific land processes included in GHGIs depend on the estimation method used, which differ in approach and complexity among countries (Supplementary Section 3). Most countries report both human-induced (direct and indirect) and natural effects on managed lands (see Table 1 and Fig. 3b). The reported estimates may then be filtered through agreed accounting rules—that is, what amount countries actually count towards their mitigation targets[15]. These may aim to better quantify the additional mitigation actions by, for example, factoring out the impact of natural disturbances[16] and of forest age-related dynamics[15,17] (Supplementary Section 1).

Under the Paris Agreement, the tracking of individual countries' progress towards NDCs will be based on their accounting approaches. However, the Global stocktake requires absolute values

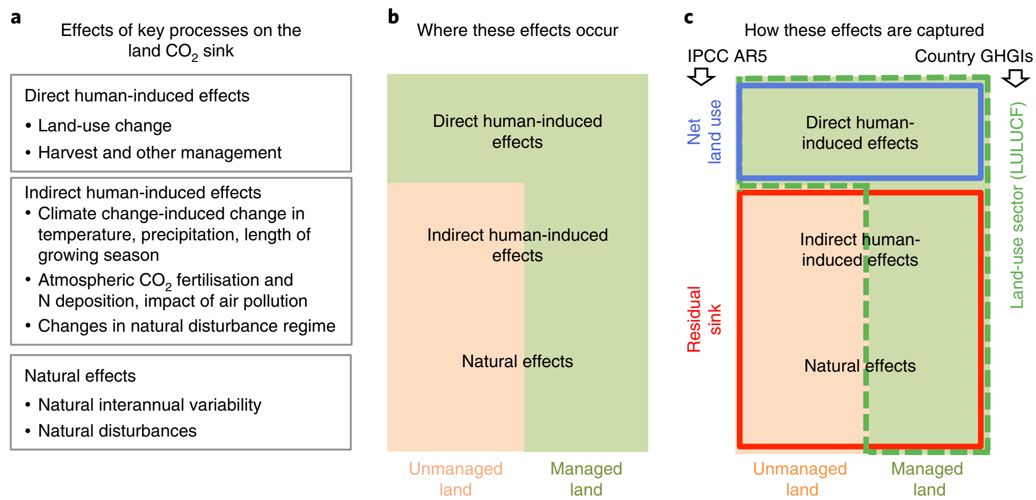

Fig. 3 | Summary of the main conceptual differences in defining the anthropogenic land CO_2 flux between IPCC AR5 and countries' GHGIs. **a**, Effects of key processes on the land flux as defined by the IPCC[12]. **b**, Land areas where these effects occur (unmanaged/primary lands versus managed/secondary lands). **c**, How these effects are captured. AR5[20,21] distinguishes the anthropogenic net land use (from ref. [8], including only direct human-induced effects) and the non-anthropogenic residual sink (calculated by the difference from the other terms in the global carbon budget[20,21]). For GHGIs the anthropogenic land flux reported to the UNFCCC (under the LULUCF sector) in most cases includes direct and indirect human-induced and natural effects in an area of managed land that is larger than the one considered by ref. [8] (see Table 1 and Supplementary Section 3).

Table 1 | Processes and effects included in the bookkeeping model, DGVMs and country GHGIs used in our analysis

	Direct anthropogenic effects			Recent indirect human-induced effects on managed/secondary forests	Natural effects on managed/secondary forests	Indirect human-induced and natural effects on unmanaged/primary forest
	CO_2 fluxes from forest land-cover change	CO_2 fluxes from harvest and regrowth	Harvested wood Products			
Bookkeeping model	x	x	x			
DGVMs (CO_2 and climate change-only runs)				x	x	x
Sum of the bookkeeping model and DGVMs	Bookkeeping model	Bookkeeping model	Bookkeeping model	DGVMs	DGVMs	
Country GHGIs	x	x	x	mostly yes[a]	x	

The bookkeeping model is from ref. [9] and includes all forest-related C fluxes (including afforestation, but excluding deforestation and peat emissions). DGVMs include results from TRENDY version 4 runs with CO_2 and climate change only (no land-use change)[22,24] from nine models: JSBACH[40], CLM4.5[41], ORCHIDEE[42], OCN[43,44], VISIT[45], JULES[46], LPJ-GUESS[47], LPJmL[48], ISAM[49]. See methods for details. [a]Among the 40 developed countries analysed (UNFCCC Annex I), we estimated that the impact of recent indirect effects on forest CO_2 fluxes is partly or mostly captured in the majority of countries' GHGIs, corresponding to 87% of the total forest net GHG flux and 73% of total managed forest area reported in the GHGIs (see Supplementary Table 2). Exceptions, that is, where recent indirect effects are mostly not captured, are Australia, Canada, Japan and a few EU countries (for example the Czech Republic, Italy, Romania, the United Kingdom). For the 50 developing countries analysed here (UNFCCC Non-Annex I), the available information suggests that the GHGIs of the most important countries in terms of forest CO_2 fluxes (that is, Brazil, China, India and Malaysia, accounting for about 70% of the net forest sink from developing countries included in this study) capture most of recent indirect anthropogenic effects (see Methods and Supplementary Table 2).

of global net anthropogenic emissions—that is, reporting of the GHG fluxes seen by the atmosphere (or expected to be seen in the future) from managed lands for each country (see Methods).

Global carbon cycle modelling community

Two fundamentally different types of global models are used to simulate the CO_2 exchange between the terrestrial biosphere and the atmosphere[18]: bookkeeping models and dynamic global vegetation models (DGVMs).

Bookkeeping models track changes in the carbon stocks of areas undergoing land-use/cover change using predefined rates of growth and decay for vegetation and soil carbon[8,19]. The bookkeeping model devised by Houghton et al.[8] has been used as the reference estimate for the anthropogenic land flux in both AR5[20,21] and the Global Carbon Project[10]. This model aims to capture only direct anthropogenic effects, including deforestation, afforestation/reforestation and wood harvest (see Methods). By keeping rates of growth and decay constant over the course of a simulation, the model attempts to exclude the indirect and natural effects from environmental changes (CO_2 fertilization, climate, N deposition, for example). However, the average biomass densities used in the model are based on relatively recent (1970–2010) observations and thus implicitly include impacts of earlier environmental changes. The global carbon budget[10,20,21] balances the bookkeeping flux from land and fossil-fuel emissions with the measured atmospheric increase and the natural response of ocean and land sinks to anthropogenic and environmental change (for example, indirect effects). Until recently[10], this natural land sink was calculated as the residual of all other terms in the carbon budget (the residual terrestrial sink).

DGVMs simulate ecosystem processes (primary productivity, autotrophic and heterotrophic respiration), their response to changing CO_2, climate, land-cover transitions and, depending on the model, additional processes such as management and natural disturbances[10,22] (see Methods and Supplementary Section 4). Within this class of models the anthropogenic and non-anthropogenic fluxes are quantified by taking the difference between model runs with and without land-cover change (and management, if modelled)[10]. Thus, the anthropogenic net land CO_2 flux includes the models' estimates of direct, indirect and in some cases natural fire effects on land that is affected by land-cover change/management. DGVMs are conceptually more similar to GHGIs in estimating the anthropogenic fluxes on a given area, but their definition of managed land is more similar to the bookkeeping approach; that is, the area experiencing management activities represented in the models.

AR5 versus GHGIs

The conceptual differences between AR5 and GHGIs in estimating the anthropogenic land flux are shown in Fig. 3c. Most GHGIs include the majority of fluxes occurring on managed lands (that is, direct, indirect and natural effects), with some differences in practice depending on methods applied (Supplementary Section 3). In contrast, AR5 disaggregates GHG fluxes into net land-use (mostly associated with direct effects in the bookkeeping model) and a residual sink (associated with responses of all land to indirect and natural effects, although some studies suggested that it is influenced by management practices[23]). Thus, in AR5 most of the indirect effects are included in the residual flux, whereas in most GHGIs they are largely included in estimated fluxes from managed lands.

Global models and the GHGIs consider fluxes from deforestation and afforestation/reforestation as direct anthropogenic fluxes but differ in the treatment of managed forests. The bookkeeping model[9], some DGVMs and GHGIs estimate land management (wood harvest and regrowth), but the managed land concept of GHGIs is broader[14] and may include management activities related to the social and ecological functions of land (Supplementary Section 1). Therefore, the managed land area considered by GHGIs is typically larger than that of global models.

Towards reconciling estimates

This study explores whether a different disaggregation and combination of the results from global models, through post-processing of existing estimates, may help to reconcile the conceptual differences described above and thus facilitate a comparison with GHGIs.

Conceptually, our framework sums the bookkeeping model estimates associated with direct effects (the AR5 anthropogenic flux, the blue box in Fig. 3c) with those associated with indirect and natural effects on managed forest (part of the AR5 residual sink, fluxes in the right part of red box in Fig. 3c). This sum is then compared with the anthropogenic forest fluxes from GHGIs (dashed green box in Fig. 3c).

Our estimates associated with direct effects are from a recent bookkeeping analysis[9], which is an updated version of AR5[8] (see Methods). We then derived fluxes associated with recent indirect and natural effects on managed forests from the post-processing of results from nine DGVMs from the TRENDY-v4 project[22,24], using model runs with CO_2 and climate change only (denoted S2; that is, without land-use change, see Methods). We used the Land-Use Harmonization dataset (LUH2-v2h, see Methods) to divide the forest flux between primary and secondary forests, assuming that secondary forests are comparable to managed forests under GHGIs and that the response of primary and secondary forests to environmental change is the same.

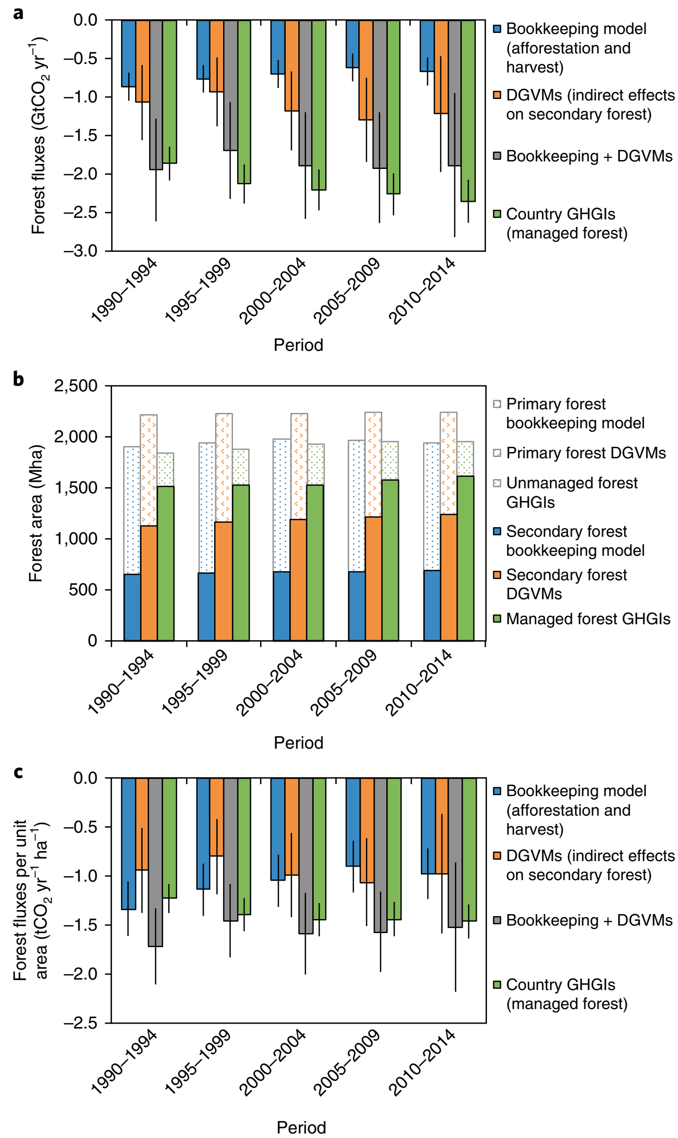

Fig. 4 | Comparison and reconciliation of developed countries' forest net CO_2 fluxes and forest area for 1990–2014. a, Net CO_2 flux from secondary/managed forests (including afforestation, but excluding deforestation). **b**, Forest area. **c**, Net CO_2 fluxes from secondary/managed forests per unit area. In GHGIs, managed forest includes the area for which countries report net emissions to UNFCCC. Secondary forest refers to areas classified as forest in the period analysed and subject to some human disturbance in the past, according to the bookkeeping model[9] or to the analysis of DGVMs (using the LUH2-v2h dataset, see Methods). The grey column in **c** (bookkeeping + DGVMs) is estimated as the grey column in **a** divided by the orange column only in **b** (secondary forest area of DGVMs), because we assume that the smaller bookkeeping secondary forest area (blue column in **b**) is already included in the DGVM secondary forest area. Error bars indicate ±1 s.d.

We first focused on developed countries (Fig. 4), which include complete time series of GHGIs for the period 1990–2014. We then provided estimates for the most important (in terms of the forest sink) developing countries and at the global level (Fig. 5), limited by data availability to the period 2005–2014. Given our focus on the forest CO_2 sink, the results presented include all existing forests (including forest management, forest regrowth, afforestation and forest degradation), but exclude deforestation and peat-related emissions (see Methods).

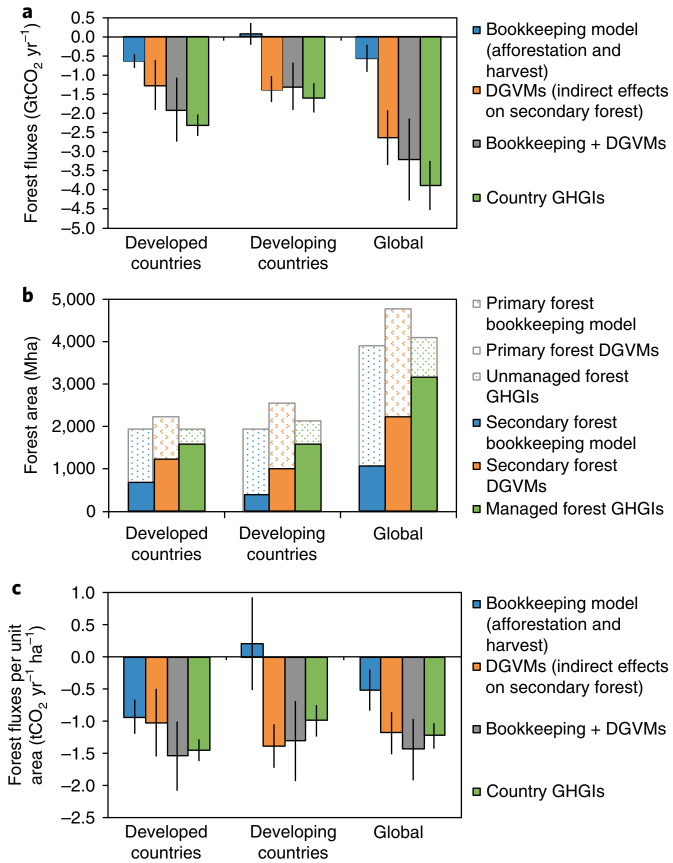

Fig. 5 | Comparison and reconciliation of global forest net CO_2 fluxes and forest area for 2005–2014. **a**, Net CO_2 flux from secondary/managed forests (including afforestation, but excluding deforestation, peat fire and peat decomposition). **b**, Forest area. **c**, Net CO_2 fluxes from secondary/managed forests per unit area. The managed forest, secondary forest and bookkeeping + DVGM columns in **c** are estimated as in Fig. 4. Although our analysis does not include all developing countries, it covers about 80% of the FAO FRA's global secondary forest area. Error bars indicate ±1 s.d.

For developed countries (Fig. 4), in the period 1990–2014 the bookkeeping estimates of net sink of secondary forests are about 1.5 $GtCO_2\,yr^{-1}$ lower than those reported in GHGIs, and show an opposite trend (Fig. 4a). The sink in the bookkeeping model slightly decreases over time, due to increasing wood harvest levels and forest aging in most countries. Deforestation fluxes (not shown in Fig. 4) are small and of similar magnitude in the bookkeeping model and country GHGIs (about 0.13 $GtCO_2\,yr^{-1}$ and 0.17 $GtCO_2\,yr^{-1}$ in the period 1990–2014, respectively). The secondary forest sink from DGVMs tends to increase over time (Supplementary Section 5), consistent with the enhanced net sink modelled in northern extratropical regions[10,22,25] that is mostly attributed to increasing atmospheric CO_2. This trend is confirmed by faster tree growth measured over the past decades (for example in Central Europe[26]), although negative impacts of environmental changes on tree growth and mortality are also observed locally[27]. When the secondary forest fluxes from DGVMs are added to fluxes from the bookkeeping model, the combined estimates (grey column in Fig. 4a) are much closer to the GHGIs. The secondary forest areas in both the bookkeeping model and the LUH2-v2h dataset are smaller than the managed forest area in GHGIs (Fig. 4b), although the total forest areas (including primary/unmanaged area) are broadly comparable. When the sum of forest CO_2 fluxes from the bookkeeping model and DGVMs is expressed on an area basis (based only on the larger secondary forest area from LUH2-v2h, see Methods), it becomes on average 13% greater than GHGI estimates (Fig. 4c). This discrepancy may be due to various factors: a possible underestimation of the sink by GHGIs because they do not fully include indirect effects, see Table 1, or the sink of pools other than biomass (see Supplementary Section 6a for a comparison with other global-level assessments[28]); the bookkeeping model including some indirect effects (Supplementary Section 3); or our post-processing of DGVMs resulting in overestimation of the forest sink.

The analysis for developing countries (Fig. 5, central columns) is less complete and more uncertain due to data limitations (see Methods). Nevertheless, the pattern that emerges is very similar to that in developed countries. First, deforestation fluxes (not shown on Fig. 5) are large, but in the period 2005–2014 have the same magnitude in the bookkeeping model (3.4 $GtCO_2\,yr^{-1}$) and in GHGIs (about 3.0 $GtCO_2\,yr^{-1}$), confirming previous analyses[7,29]. Second, the wide discrepancy (about 1.6 $GtCO_2\,yr^{-1}$) between the bookkeeping model and GHGIs is largely reconciled by considering indirect effects on secondary forests in DGVMs (Fig. 5a). The small net source estimated by the bookkeeping model is mainly due to increasing rates of wood harvest (often associated with forest degradation) offsetting the sink in forest expansion and regrowth. When differences in areas are taken into account (Fig. 5b), the sum of the bookkeeping model and DGVMs is 30% greater than GHGI estimates (Fig. 5c).

The global-level analysis indicates that the discrepancy in land-related fluxes between the bookkeeping model and GHGIs (about 4 $GtCO_2\,yr^{-1}$ in the period 2005–2014 using updated estimates, Fig. 2) is associated mostly (80%, or 3.2 $GtCO_2\,yr^{-1}$, Fig. 5a, right columns) with managed forest sink estimates, and not with deforestation. The remaining 20% is probably due to non-forest land uses (for example crops, pastures), which are considered by the bookkeeping model and only partially by GHGIs, and to other processes (for example peat fires, peat decomposition). The gap in forest fluxes can be largely reconciled when differences in the consideration of indirect effects and managed forest areas are taken into account (Fig. 5); this is also confirmed by a number of detailed country case studies (Supplementary Sections 6b and 6c). Other factors, not explored here, may contribute to the discrepancy in forest fluxes—for example, different forest definitions, legacy effects, data sources and methods[7,18,19,30,31] (Supplementary Section 5). The impact of these factors could be explored further in future updates of our analysis, for example, by extending the comparison of country data with other datasets (for example, ref. [29,32,33]) and including other bookkeeping models[19] and updated DGVM results. However, it is unlikely that these factors and additional analyses would contradict our main conclusions.

Policy implications and roadmap

This study highlights the main reasons for the large discrepancy in the global net anthropogenic land CO_2 flux estimates between the bookkeeping model[9] used by AR5 and country GHGIs (about 4 $GtCO_2\,yr^{-1}$ for the period 2005–2014 using updated estimates, Fig. 2), and outlines a feasible method to resolve this discrepancy. The outcomes of our study are relevant for both IPCC programmes (the Special Report on Climate Change and Land and AR6) and the Paris Agreement's Global stocktake.

We show that globally about 80% of the above discrepancy (3.2 $GtCO_2\,yr^{-1}$) is related to conceptual differences in anthropogenic forest sink estimates, in both developed and developing countries. Country GHGIs often include estimates from large areas of managed forests and the impact of indirect effects (environmental change). Global models, in contrast, estimate the anthropogenic land flux by considering fewer management activities on a smaller managed forest area, and include most of the indirect effects on extant forests in the residual (non-anthropogenic) land response.

A simple post-processing approach, disaggregating the results of global models, increases their comparability with GHGIs (Figs. 4 and 5, Supplementary Section 7).

Although differences in scope, methods and datasets will probably preclude complete reconciliation of global model and GHGI estimates, improvements on both sides can help in better understanding and attributing differences. This leads to the specific recommendations below, for both GHGIs and global models.

Country GHGIs should provide more transparent and complete information on managed forests, including maps, harvested area, harvest cycle, forest age and if/how indirect and natural effects are included. The refinement of the IPCC Guidelines (expected in 2019) could help by documenting how different methods and data incorporate direct and indirect human effects in the reported estimates (Supplementary Section 3). As the bookkeeping model[9] uses forest data submitted by countries to the FAO, it is crucial that countries report consistently to the UNFCCC and FAO, which is not always the case at present[31]. The voluntary inclusion of information on non-anthropogenic fluxes from unmanaged lands in national reporting, although not used for accounting purposes, would help us to better understand the responses of terrestrial ecosystems to climate change, including processes in unmanaged land (for example, fires, permafrost thawing) that are relevant for assessing progress towards the goals of the Paris Agreement.

In parallel, the global modelling community should design future models and model experiments to increase their comparability with historical GHGIs and thus their relevance in the context of the Paris Agreement. For example, through more disaggregated model results (such as sinks from both primary and secondary forests in each grid cell) and clear information on the areas involved, the analysis proposed here could be used to identify the anthropogenic components of the land flux. Efforts to improve estimates should include a better representation of management[34,35] and natural disturbances in global models.

The above also applies to modelling future net emission pathways from integrated assessment models[36], which are used to assess the collective gap between current country mitigation ambition and a well-below-2 °C pathway. These models take the same approach to anthropogenic fluxes as the bookkeeping model[9], and thus tend to estimate lower anthropogenic forest sinks and higher net anthropogenic land emissions than country GHGIs (Fig. 1b). Even if these discrepancies can be harmonized[37] or corrected for, they may increase the uncertainty of the emission gap[38]. Following the more systematic approach developed here, reallocating the environmentally driven fluxes from managed land (currently a part of the residual terrestrial sink) to the anthropogenic net land flux (see Supplementary Section 8) would increase their comparability and consistency with country mitigation targets. This reallocation would minimize the need for ad hoc land-related corrections, therefore reducing the uncertainty of the emission gap without affecting the decarbonization pathways that are consistent with the Paris Agreement[3].

In summary, our study highlights that estimates of the anthropogenic forest sink in countries' GHGIs and global models (reflected in AR5) are not conceptually comparable. The magnitude of the differences may jeopardize the intent of the Global stocktake to assess collective progress towards the targets of the Paris Agreement. To minimize this risk, the forthcoming AR6 will need to assess available literature that provides results with a greater level of disaggregation[39]. In addition, countries will need to increase the transparency of their GHGIs, including how estimates incorporate indirect human and natural effects in managed lands. Ultimately, greater collaboration between the scientific communities that support the IPCC assessment reports and the GHGIs is needed to increase confidence in land-related GHG estimates for the assessment of collective progress towards the goals of the Paris Agreement.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0283-x.

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Author contributions

G.G. designed the analysis with J.H. and W.A.K., and all three drafted the manuscript. G.G. coordinated all of the inputs, executed the calculations and made the figures. A.C., R.A.H., G.P.P. and M.J.S. contributed to the analysis and provided inputs to the manuscript. F.D. contributed by commenting and editing the manuscript. R.A.V., S.R., S.F. and D.L. contributed to collecting data and information on country GHGIs. R.A. post-processed the DGVM results. R.A.H. and A.A.N. provided data from bookkeeping models. L.P. provided comments on the Global stocktake. A.A., A.B., M.F., P.F., A.K.J., E.K., C.D.K., J.E.M.S.N., S.S., N.V., A.W. and S.Z. provided the original DGVM results and inputs to the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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Methods

Inputs to the Global stocktake. According to Article 14 of the Paris Agreement[1], collective progress towards holding the increase in the global average temperature to well below 2 °C above pre-industrial levels (Article 2 of the Paris Agreement) will be assessed periodically (every five years starting in 2023) by the Global stocktake. This temperature goal requires reaching a "balance between global anthropogenic greenhouse gas emissions by sources and removals by sinks in the second half of this century" (Article 4 of the Paris Agreement)[1]. A close comparison of Article 4 with other UNFCCC documents points to the exclusion of natural sinks[2], suggesting that this balance is referring to achieving net zero anthropogenic GHG emissions[52].

To support the Paris Agreement, and particularly the Global stocktake, the IPCC will release an ambitious set of documents, including the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, three special reports (on 1.5 °C, land and oceans, to be completed in 2018 and 2019) and AR6 (in 2022).

In light of the available information (paragraphs 99–101 of UNFCCC Decision 1/CP.21[1] and related countries' submissions[53]), this study assumes that the mitigation part of the Global stocktake will be based on two main sources of input. The first comprises globally aggregated country data on anthropogenic net emissions, either from existing GHG reporting obligations or expected under the Framework for transparency of actions (see Supplementary Section 1), including GHGIs in the National Inventory Reports (NIRs) and Biennial Update Reports (BURs) for assessing the historical period, and National Communications (NCs) and Nationally Determined Contributions (NDCs) for the forward-looking assessment. The second source is independent scientific estimates (including estimates summarized in AR6) of historical anthropogenic net emissions and future well-below-2 °C emission pathways. We assume that the independent scientific estimates will be used as a benchmark against which the aggregated country data will be assessed to identify the emissions gap[51,54,55]. Consistent with this assumption, in 2022 (that is, in time to be used by the Global stocktake) the contribution of Working Group III to AR6[39] is expected to provide anthropogenic emissions and removals in each of agriculture, forestry, other land uses, emissions from non-managed terrestrial ecosystems and their implications for mitigation pathways. The information on non-managed land is important because such lands can contribute substantial climate sinks and feedbacks (such as thawing of permafrost[56]), affecting the long-term climate goals.

We further assume that country GHG data will be extracted (and summed up at global level) from the land-use, land-use change and forestry (LULUCF) reporting of the total net land flux in managed lands, rather than from the accounting, which refers to the comparison of net emissions due to mitigation actions with the agreed country mitigation targets[57]. For LULUCF, the accounting filters flux estimates through negotiated accounting rules, which aim to reflect only the impact of individual countries' mitigation actions[15].

For assessing collective progress towards the balance between GHG emissions and removals, the Global stocktake will require globally aggregated values of absolute net anthropogenic land GHG emissions, that is, as reported by countries for managed lands and not filtered by accounting rules. For the historical period, GHG estimates will be available in the NIRs submitted by each country as per Article 13.7(a) of the Paris Agreement. For the forward-looking assessment, these absolute values need to be extracted from the NDCs or country projections, which may have applied specific accounting rules (Supplementary Section 1) that may affect the estimated fluxes[5]. For example, a country may use a forest reference level (that is, a benchmark of forest net emissions expected under business-as-usual activity against which the future net emissions due to mitigation activity will be compared[15]) to quantify the forest mitigation contribution towards its 2030 NDC target. For a case in which the areas of managed forest are already a sink and are expected to still act a net sink in 2030 without any change in management, the forest may not deliver additional mitigation in 2030 (relative to the reference level). Therefore, although the forest accounting in the NDC may be zero, the Global stocktake will need to consider the absolute forest sink expected to be included in the reporting for 2030. In this context, it is key for countries to provide disaggregated and transparent information on how LULUCF is included in its NDC, such that the expected changes in absolute values of fluxes can be extracted.

Country data submitted to the UNFCCC. A general description of country GHGI estimation, reporting, accounting and review under the UNFCCC is included in Supplementary Section 1.

Global LULUCF country CO_2 data in Fig. 2 (1990–2014) are updated to February 2016 (from ref. [5], dashed green line), or updated to June 2018 for this study (solid green line). The recent update includes new CO_2 data from the 2018 GHGIs of all UNFCCC Annex I countries[58] (broadly defined in this paper as developed countries) and from the BURs[59] and NCs[60] of several Non-Annex I countries (broadly defined in this paper as developing countries), including Brazil, China, Indonesia and Malaysia. Note that some of the developing country data in Fig. 2 include some non-CO_2 emissions. However, this contribution is assumed to be very small; for example, for developed countries, the non-CO_2 emissions are around 2–4% of the total CO_2-equivalent forest sink[7].

Our study mainly focuses on the forest CO_2 fluxes of developed countries (Fig. 4), most of which have considerable experience in constructing GHGIs and more detailed and robust information than many developing countries. However, to highlight the global relevance of our analysis, forest CO_2 flux estimates from developing countries are also shown in Fig. 5 for the period 2005–2014. Although the lack of specific forest CO_2 flux data in many developing countries prevents us from providing a complete global analysis, our study is globally relevant because global data in Fig. 5 cover about 80% of the global secondary forest area recognized in the FAO Forest Resources Assessment (FRA) (66% for developing countries only). The methods used to collect forest CO_2 estimates from developed and developing countries (as shown in Figs. 4 and 5) are outlined below.

Developed countries. The following 40 countries were included in this study (Supplementary Table 4): Australia, Belarus, Canada, the EU (28 countries), Japan, Kazakhstan, New Zealand, Norway, Russia, Switzerland, Turkey, Ukraine and the United States. The 1990–2014 time series of forest CO_2 estimates used in this study (Fig. 4) are taken from the GHGIs submitted in 2018[58], and include the following categories from the LULUCF sector: forest land (including 'forest remaining forest' and 'land converted to forest'), harvested wood products and forest fires. Estimates for deforestation are from 'forest converted to all other land uses'. Although GHGIs include all GHGs, we considered only CO_2 to allow comparability with the other datasets used in this study. The main sources of non-CO_2 forest emissions are forest fire (CH_4 and N_2O) and emissions associated with the loss of forest soil organic matter (N_2O).

All developed countries use the 2006 IPCC Guidelines for estimating fluxes in their GHGIs, which implies the use of the managed land proxy (see Supplementary Section 1), even if this concept is explicit for only a few GHGIs[14] (for example, the United States, Canada, Russia; in most EU countries all land is implicitly reported as managed). We estimated that the impact of recent indirect anthropogenic effects is included in the large majority of developed countries' GHGIs (see Table 1 and Supplementary Table 2).

Developing countries. Data in Fig. 5 include forest CO_2 estimates only, including afforestation, regrowth and forest degradation, but excluding emissions from deforestation, peat fires and peat decomposition. Given the high uncertainty in the data from many developing countries, we applied a number of filters. First, we considered only recent (post-2014) information from BURs[59], NCs[60] and REDD+ submissions[61]. In a few cases, gaps in forest area data where filled using data for 'secondary' and 'planted' forests from FAO FRA 2015 data, see Supplementary Table 5. Second, we used estimates only for the 2005–2014 period (where only one or two data points were available, we considered this data to be representative for the whole period). Third, we selected only data estimated using the 2003 IPCC Good Practice Guidance or the 2006 IPCC Guidelines for the forest land category of BURs or NCs, or for the relevant activities of the REDD+ submissions (that is, forest degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks, all of which we considered as part of the forest land category).

After the filters above were applied, we were able to collect forest CO_2 flux estimates from about 50 developing countries (see Supplementary Table 5), including Argentina, Brazil, Chile, China, Colombia, Congo, Costa Rica, Ecuador, Ethiopia, Georgia, Ghana, India, Indonesia, Kenya, Lao, Malaysia, Mexico, Mongolia, Namibia, Nepal, Papua New Guinea, Paraguay, the Republic of Korea, South Africa, Swaziland, Tunisia, Uganda, Uruguay, Venezuela and Vietnam (plus other smaller countries).

The use of either 2003 or 2006 IPCC methodological guidance implies that the managed land proxy was employed, even if rarely mentioned (for example, Brazil[14]). Several developing countries do not report unmanaged lands[31], implicitly considering all forests as managed. Due to frequent lack of precise methodological information, it is difficult to draw precise conclusions on the role of indirect anthropogenic effects on GHGI estimates for many developing countries. Nevertheless, on the basis of the available information (see Supplementary Section 3, Supplementary Table 6, countries' GHGIs and ref. [31]) we conclude that the GHG data of the most important developing countries (in terms of forest CO_2 sinks or area, that is China, Brazil, India and Malaysia, corresponding to about 70% of the forest sink of developing countries in Fig. 5a) capture most or all recent indirect anthropogenic effects.

Although many developing countries report some data on LULUCF net emissions[5], few explicitly report emissions from deforestation. An approximate estimate of emissions from deforestation in developing countries for the period 2005–2014 was derived by taking their total LULUCF emissions (around 2 $GtCO_2\,yr^{-1}$, based on an update of ref. [5]) and then subtracting their net forest CO_2 flux from GHGIs estimated above (around 1.6 $GtCO_2\,yr^{-1}$ including the forest land category but excluding deforestation, see Fig. 5a, central green column) and the emissions from peat fires and decomposition (around 0.6 $GtCO_2\,yr^{-1}$, reported by Indonesia). This approach simplistically assumes that net emissions from non-forest land uses are negligible.

The uncertainty of GHGIs (±1 s.d.) in Figs. 4 and 5 is based on the information reported in countries' GHG reports, following the methodology described in the supplementary information of ref. [5]. According to this information, the uncertainty of forest-related fluxes (expressed as the 95% confidence interval, and often including deforestation) is approximately 25% for developed countries and 40% for developing countries. An uncertainty of 60% was assumed for all those developing countries for which no information on uncertainty was available. This information was then converted into ±1 s.d. for this paper.

Bookkeeping model. Houghton and colleagues' bookkeeping model was first developed more than 30 years ago[62]. It has been used since then to track changes in terrestrial carbon stocks as a result of land-use and land-cover change (LULCC). The most recent analysis[9] includes six types of land management since 1850: conversion of native ecosystems to croplands, to pastures and to plantation forests (and the recovery of native systems following abandonment); harvest of industrial wood and fuelwood; and fire management (in the United States and southeast Asia). The approach does not include natural disturbances. Data for annual changes in agricultural areas and harvests are obtained from the FAO after 1960 and from other, varied sources between 1700 and 1960[9].

The model tracks four pools of carbon for each hectare managed or disturbed: living biomass (above- and belowground), dead biomass (or slash) generated as a result of disturbance, harvested wood products and soil organic carbon (affected only by cultivation). Some of the losses of carbon occur in the year of disturbance (burning), and some occur over years to decades (soil carbon, slash and wood products).

Rates of growth and decay for 20 types of ecosystems are based on field measurements for the 1970–2010 period. The rates vary among ecosystem types but are constant through time. That is, rates of growth and decay are the same in 1850 as they are in 2015. That assumption was an attempt to include only the effects of anthropogenic management, and to exclude the effects of environmental change, for example, CO_2 fertilization, climate or N deposition. Using those rates presumably leads to small overestimates of biomass and growth at the beginning of a simulation and an underestimation towards the end of a simulation.

The net and gross emissions of carbon from LULCC are driven by LULCC activities in individual countries. Within countries the model is non-spatial. Native ecosystems that are not converted or harvested are assumed to be neutral with respect to carbon balance. Thus, the estimated emissions of carbon refer to explicit anthropogenic changes in land cover and management (wood harvest).

Data from ref. [9] used in this study include only CO_2 emissions from the following categories: forest conversion to cropland or abandonment of cropland back to forest; forest conversion to pasture or abandonment of pasture back to forest; forest loss that is unexplained by gains in cropland and pasture and is converted to crops and then subsequently abandoned back to other land in the form of regrowing forest; forest or other land converted to planted forest; industrial wood harvest; fuelwood harvest; and fire emissions (for only the United States among developed countries).

The values of uncertainty (±1 s.d.) in Figs. 4 and 5 are based on the values reported by ref. [9] for the regions corresponding to developed and developing countries. It should be noted that it was not possible to calculate the standard deviation after 1990, and the estimated values for individual regions refer to the period 1950–1990[9].

DGVMs. AR5[21] and the Global Carbon Project (GCP)[10] assess land model intercomparisons that have been coordinated by the Trends and drivers of the regional-scale sources and sinks of carbon dioxide project (TRENDY[24]; http://dgvm.ceh.ac.uk/node/9). The DGVMs were forced with historical data for climate, atmospheric CO_2 concentration, N deposition and land-cover transitions. Some DGVMs include forest management (for example, wood harvest) in the simulations (for example, refs [34,35,49]).

The TRENDY v4 models[24] were forced with a reconstruction of the land use, either the HYDE dataset of cropland and pasture distributions[63], or the LUH-v1[64] dataset, which is based on HYDE but provides annual, half-degree, fractional data on land-cover distribution, including cropland, pasture, primary forests and secondary forests (as well as all underlying transitions between land-use states) in addition to wood harvest and shifting cultivation. The HYDE data are based on annual FAO statistics of change in agricultural area[65]. For the period 2011–2013, the HYDE dataset was extrapolated by country for pastures and cropland separately based on the trend in agricultural area over the previous five years. The HYDE dataset is independent from the dataset used in the bookkeeping model[9], which is based primarily on forest area change statistics. Furthermore, although the LUH2-v1 dataset distinguishes forested and non-forested land (based on a separate underlying global model[64]) and indicates whether land-use changes occur on forested or non-forested land, typically only the changes in agricultural areas are used by the models and are implemented differently within each model (for example, an increased cropland fraction in a grid cell can either be at the expense of grassland, or forest, the latter resulting in deforestation; land-cover fractions for the non-agricultural land differ between models). Thus the DGVM forest area and forest-area change over time is not consistent with the FAO's forest area data used for the bookkeeping model to calculate emissions from land-use change. Similarly, model-specific assumptions are applied to convert deforested biomass or deforested area, and other forest product pools, into carbon in some models.

DGVMs typically classify vegetation into broad plant functional types and use average characteristics of each type within coarse-resolution grid cells (0.5° or coarser). Not all TRENDY models simulate wood harvest or fire, and most do not simulate forest age-class distributions (see Supplementary Table 7).

In this study, we used the TRENDY data to assess the impact of indirect effects in managed forest land (excluding land-use change and harvest, already captured in the bookkeeping model). The model run relevant to our study is S2; environmental change only (climate, CO_2 fertilization and N deposition, but no land-cover change or management). We post-processed the results from nine DGVMs in the framework of the TRENDY-v4 project[24]. Note that in the current version of TRENDY only the JSBACH and ISAM models provide forest net biome productivity (NBP) separately from other vegetation NBP, and the other models give total NBP in the grid cell. For these other models, we computed the total NBP per unit of area, at grid-cell level (from S2 model runs), and then assumed that forest NBP equals total NBP (that is, assume that non-forest NBP is negligible). Although this assumption is crude, it is supported by several lines of evidence. At the global level, ref. [28] concluded that "within the limits of reported uncertainty, the entire terrestrial C sink is accounted for by C uptake of global established forest" and consequently, "non-forest ecosystems are collectively neither a major C sink nor a major source over the two time periods that we monitored". For developed countries (that is, the main focus of our study), the analysis of countries' GHGIs indicates that when emissions associated with land-use changes are excluded, forest NBP is slightly greater (by 10%) than total NBP (including cropland, grassland, wetland and so on). Overall, this suggests that on a large scale non-forest NBP is likely to be small relative to forest NBP.

We assumed primary and secondary forest as defined in the land-use harmonization dataset (LUH2-v2h, http://luh.umd.edu/data.shtml) were conceptually comparable to unmanaged and managed forest, respectively. Secondary forest in the LUH2-v2h datasets refers to land that was previously disturbed by human activities (post-AD 850) and recovering. We therefore extracted the fraction of primary and secondary forest area per grid cell from the LUH2-v2h dataset. Finally, the forest NBP provided by the different DGVMs was separated into fractions originating from secondary and primary forests using the LUH2-v2h area fractions. Grid cells that had no forests during the period 1990–2014 in the LUH2-v2h dataset were excluded from the analysis. This approach implicitly assumes that within each grid cell the response of primary and secondary forests to environmental change is approximately the same. To our knowledge, there is no scientific evidence supporting other assumptions.

The approach above would be improved if DGVMs were to provide more disaggregated outputs (NBP from primary and secondary forests in each grid cell), or if more sophisticated approaches are developed to separate ex-post forest NBP from total NBP. Models that explicitly include age classes and/or secondary forest could provide a more specific description of LULCC transitions.

The ensemble used in this study includes the following nine models: ORCHIDEE[42], OCN[44], JULES[46], CLM4.5[41], JSBACH[40], VISIT[45], LPJ-GUESS[47], LPJmL[48] and ISAM[49]. The main characteristics of these models are summarized in Supplementary Table 7.

The original runs of these models were performed at different spatial resolutions, ranging from 0.5° to 1.875° (Supplementary Table 7). To be consistent with the LUH2-v2h dataset, all model outputs were resampled to a spatial resolution of 0.25° × 0.25° using the first-order conservative remapping approach[66].

The values of the uncertainty (±1 s.d.) in Figs. 4 and 5 are based on the values of net forest flux reported by individual DGVMs.

When the sum of forest CO_2 fluxes from the bookkeeping model and DGVMs is expressed on an area basis (Figs. 4c and 5c), we used the larger secondary forest area from LUH2-v2h, assuming that the smaller bookkeeping secondary forest area is already included in LUH2-v2h.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks

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SUPPLEMENTARY INFORMATION

Reconciling global model estimates and country reporting of anthropogenic forest CO_2 sinks

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Sections 1-4 provide additional methodological information and data on: how country GHG inventories (GHGI) are estimated, reported, accounted and reviewed under the UNFCCC (Section 1); country GHG data for 2005-2014 (Section 2); how anthropogenic effects are captured by GHG inventories and by Houghton's model (Section 3); characteristics of the DGVMs used in this study (Section 4).

Sections 5-8 include additional analysis and results on: forest net CO_2 fluxes by each DGVM, and long-term estimated trends (Section 5); the comparison of GHGIs with other studies (Section 6a), and with the Houghton's bookkeeping model and DGVMs for country case studies (Section 6b for EU, Russia, USA; Section 6c for Brazil and China); the proposed disaggregation of forest-related estimates from global models and implications for historical GHG estimates (Section 7); and the conceptual implications of our analysis for the 2^{o}C trajectory (Section 8).

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1. Overview of forest GHG estimation, reporting, accounting and review under the UNFCCC

1a) GHG estimation and reporting by countries

All signatories to the United Nations Framework Convention on Climate Change (UNFCCC, 197 Parties have ratified the Convention, i.e. 196 countries plus the European Union) are required to report national data with estimations of greenhouse gas (GHG) emissions and removals through the submission of national GHG inventories (GHGIs)[1]. GHGIs cover all economic sectors, including: energy; industrial processes; agriculture; land use, land-use change and forestry (LULUCF), and waste. Emissions and removals from forests are part of the LULUCF sector. Current GHGI reporting requirements differ between UNFCCC "Annex I countries" (OECD countries as in 1998 and economies in transition, broadly defined in this paper as "developed countries"), and "Non Annex I countries" (all the remaining signatories, broadly defined in this paper as "developed countries") in terms of frequency and quantity of information to be reported (Tab SI 1).

Table SI 1. UNFCCC requirements for the reporting of GHGIs

UNFCCC "Annex I" ("developed") countries	**UNFCCC "Non-Annex I" ("developing") countries**
National communication (NC, every 4 years)*	National communication (NC, every 4 years)
Biennial Report (BR, every 2 years)*	Biennial Update Report (BUR, every 2 years)*
National Inventory Report (NIR, annually)*	

**Reports that undergo review procedures (see Section 1c below)*

Annex I countries submit National Inventory Reports (NIRs)[2] annually, in addition to reporting through National Communications (NCs) and Biennial Reports (BRs), all of which are independently reviewed or assessed following UNFCCC guidance. For Non-Annex I countries, the GHGI is included as a chapter in the NCs[3], and from 2014 a summary of the GHGI is also included in the Biennial Update Reports (BURs)[4]. Developing countries aiming at accessing result-based payments for REDD+ (Reducing Emissions from Deforestation and forest Degradation, plus other forest-related activities) results, may also submit[5], voluntarily, reference (emission) levels and a REDD+ annex to their BURs, which include information on forest-related fluxes only.

Countries are expected to estimate anthropogenic GHG fluxes (emissions and removals) using Guidelines (and Good Practice Guidance) provided by the IPCC's Task Force on National Greenhouse Gas Inventories (TFI). The TFI is tasked by UNFCCC with developing internationally-agreed methodologies for the estimation of GHG emissions and removals and to encourage the widespread use of such methodologies in order to ensure comparability of GHG estimates across sectors and countries. To ensure comparable estimates, all countries are required (developed countries) or encouraged (developing countries) to follow the latest IPCC guideline. The latest available IPCC methodological guideline is the “2006 Guidelines for National Greenhouse Gas Inventories”[6], for which a Refinement will be available in 2019.

A major methodological concern for the LULUCF sector is the difficulty in separating the impact of “direct human-induced” from “indirect human-induced” and “natural” effects on CO_2 fluxes. In 2001, the Marrakesh Accords decision 11/CP.7 on Land Use, Land-Use Change and Forestry (LULUCF) invited the IPCC to ‘‘develop practicable methodologies to factor out direct human-induced changes in C stocks and greenhouse gas emissions by sources and removals by sinks from changes … due to indirect human-induced and natural effects (such as those from carbon dioxide (CO_2) fertilization and nitrogen (N) deposition), and effects due to past practices in forests (pre-reference year)”. The issue was included to ensure the development of appropriate and fair accounting rules (see also SI section 1b) for future use under the Kyoto Protocol, i.e. rules that would exclude credits resulting from indirect effects of human action or global change, or from activities undertaken in the past prior to accounting reference periods[7–9].

Two IPCC expert groups analyzed the issue in 2002 and 2003[10,11] and concluded that at that time the state of science was insufficient to develop practicable and sound scientifically-based methodologies to appropriately separate direct and indirect human-induced effects from natural effects on terrestrial carbon sinks and sources within the timeframe requested in the Marrakesh Accords. As a result of this, the IPCC adopted the “managed land” concept[6,12] as a pragmatic proxy to facilitate GHGI reporting. “Anthropogenic” land GHG fluxes 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”[6]. The underlying assumption is that the majority of anthropogenic GHG fluxes (direct and indirect) take place on managed lands and that the net contribution from natural effects is negligible over time. A third expert group was convened in 2010[13] and essentially came to similar conclusions, reconfirming the “managed land” proxy as the “only universally applicable approach” to estimate anthropogenic emissions and removals in the LULUCF sector, despite the recognised shortcomings of this approach[13].

At the same time, the IPCC Guidelines allow for accommodation of national circumstances, such as defining land uses (e.g., what is a forest) or determining what areas of the country are ‘managed’ lands (Tab. SI 2). All land definitions and classifications are specified at the national level, and “should be described transparently and applied consistently over time”.

The IPCC Guidelines implicitly recognize country differences in capacities or availability of data, and provide a range of different “tiers” of methodological complexity and data requirements that allow for progressive improvements. Tier 1 is the basic method and is “designed to use readily available national or international statistics” combined with provided default values and “therefore should be feasible for all countries”. Higher Tier 2 and 3 methods may involve locally developed parameter datasets, more spatially and temporally disaggregated datasets and model based approaches.

Table SI 2. Areas of managed and unmanaged forests for the main countries (in terms of forest sink or area) analyzed in this study, and definition of managed forest.

<table>
<tr><th rowspan="3"></th><th colspan="2">Forest area (Mha) [1]</th><th colspan="4">Definition of managed forest (if available), from countries reports to UNFCCC[1].</th></tr>
<tr><th rowspan="2">Managed</th><th rowspan="2">Unmanaged</th><th colspan="3">Quantitative Thresholds</th><th rowspan="2">Qualitative information</th></tr>
<tr><th>Min. land area (ha)</th><th>Min. crown cover (%)</th><th>Min. height (m)</th></tr>
<tr><td>Australia</td><td>132</td><td>-</td><td>0.2</td><td>20</td><td>2</td><td>Forest land includes all lands with a tree height of at least 2 meters and crown canopy cover of 20 per cent or more and lands with systems with a woody biomass vegetation structure that currently fall below but which, in situ, could potentially reach the threshold values of the definition of forest land. Young natural stands and all plantations which have yet to reach a crown density of 20 per cent or tree height of 2 meters are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of either human intervention, such as harvesting, or natural causes, but which are expected to revert to forest. Forest land does not include woody horticulture which meets the forest threshold parameters; this land is classified as croplands. A map of forests is available in the NIR.</td></tr>
<tr><td>Canada</td><td>226</td><td>122</td><td>1</td><td>25</td><td>5</td><td>For the purpose of the GHG inventory, managed forests are those managed for timber and non-timber resources (including parks) or subject to fire protection. A map of forests is available in the NIR.</td></tr>
<tr><td>EU</td><td>163</td><td>3</td><td colspan="4">A compilation of country specific information for the 28 EU countries and Iceland is included in the EU's GHGI (https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2017) In most countries forests are areas larger than 0.5 ha, with a minimum crown cover of 10% and where the trees have reached at least 5m. Some EU countries also use a minimum width, often of 20m, to define forest areas. For some countries with large forest areas, these quantitative thresholds can be different and include smaller areas, or areas where the height and crown cover of the stand are smaller. In addition, most of the EU countries declare that unstocked areas that currently fall below, but that are expected to exceed, the forest's thresholds, are also included in the definition of forest. Also forest infrastructures (e.g. forest roads, firebreaks) are typically included under forest area.</td></tr>
<tr><td>Russia</td><td>685</td><td>212</td><td>1</td><td>18</td><td>5</td><td>Managed forests are defined as forests in which systematic human activities are carried out to fulfill the necessary social, economic and ecological tasks to ensure rational, continuous and sustainable forest management, reproduction, protection and monitoring of forests. This includes any area with an organized set of economic activities in forests such as: conducting of regular forest inventories, long-term planning, determination of annual allowable cut and accounting for their economic purpose and environmental functions, as well as forest protection and reforestation activities that ensure the stabilization and reduction of forest losses from fire and other disturbances. Forest reserves are excluded. A map of managed forest is available in the NIR.</td></tr>
<tr><td>USA</td><td>293</td><td>9</td><td>0.4 (36.6 m wide)</td><td>10</td><td>5</td><td>All forest lands with active fire protection, accessible to roads and other transportation, or protected for recreational or conservation purposes are considered managed—therefore, all forests within the "lower 48" (continental US) are considered managed. In Alaska, managed areas include: a 10-km buffer around settlements, roads and train corridors; lands with active or past resource extraction, including a 3,300 meter buffer around petroleum extraction and 4,000 meters around mining sites; lands with active fire management; and protected areas where there is active management for resource extraction, recreation or to suppress natural disturbances. The remaining lands in Alaska are considered 'unmanaged', i.e. inaccessible to society due to the remoteness of the location, and comprise around 3% (46 million ha) of the US land base and include 8.6 million ha of forest land. The 2015 NIR included a map of managed and unmanaged forest areas; since then, small adjustments have been made to managed areas in Alaska which are described in the more recent NIRs.</td></tr>
<tr><td>Brazil</td><td>234</td><td>258</td><td colspan="4">Brazil is a country of continental dimensions and with a large diversity of forest types. The forest definition broadly applicable in Brazil is that reported to the FAO for the Global Forest Resources Assessments (FRA): "Forest is defined as land spanning more than 0.5 hectare with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. Land not classified as "Forest", spanning more than 0.5 hectare; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10% classified as "Other Wooded Land". These two categories (Forest and Other Wooded Land) do not include land that is predominantly under agricultural or urban land use.
Managed Areas comprise Protected Areas (PAs) and Indigenous Lands (IL). In the period 1994-2002 the managed areas share has increased due to more information now available on indigenous lands (e.g. managed areas in the Amazon biome increased from 23.7% to 48.9%).</td></tr>
<tr><td>China</td><td>208</td><td>NE</td><td colspan="4">Forest Land is defined as a land having minimum area of 0.67 ha. Trees must have a minimum crown cover of 20% and a minimum tree height of 2m.</td></tr>
<tr><td>India</td><td>70</td><td>NE</td><td colspan="4">Forest includes all lands, more than one hectare in area, with a tree canopy density of more than 10% irrespective of ownership and legal status. It also includes orchards, bamboo and palm.</td></tr>
</table>

[1] For developed countries, information is taken from NIRs 2017 (areas are for the year 2015). For developing countries, information (referring to ≈ 2010) is taken from: Brazil's 3rd NC (2016) and REDD+ Submission (2015), China's BUR (2017), and India's BUR (2016).

In addition to differences in the data quality and methods used to compile national GHGIs, there are also differences in the level of comprehensiveness in coverage of land-use categories (e.g., grasslands, wetlands) and within categories (e.g. reporting of all carbon pools and non-CO_2 GHG)[14]. Most developed countries' inventories, over time, have become relatively complete in estimating forest-related fluxes on most carbon pools (see Figure SI 1), with clear improvements especially on land converted to forest.

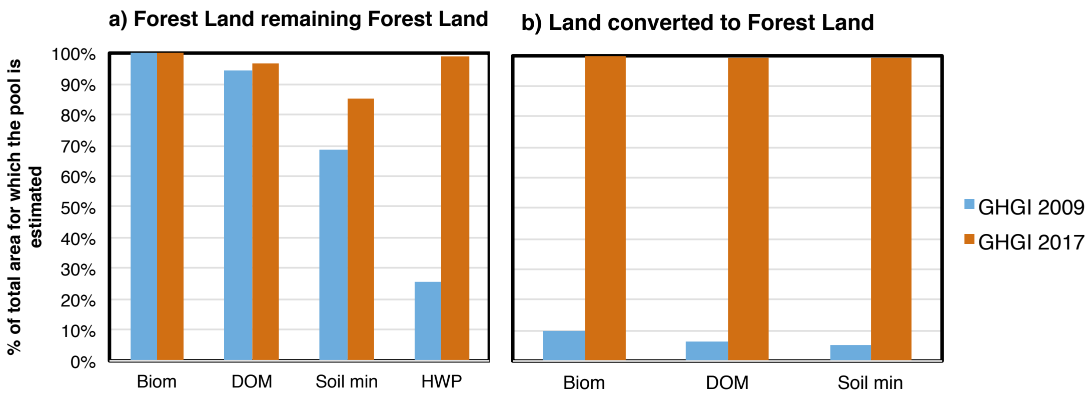

Figure SI 1. Percentage of total area of UNFCCC Annex I countries for which GHG are reported estimates in individual carbon pools. The carbon pools are: Biomass, Dead Organic Matter, Mineral Soil, Harvested Wood Products. Categories (a) "Forest land remaining forest land" (i.e., forest having remained forest for at least 20 years) and (b) "Land converted to forest land" (areas converted to forest in the last 20 years), from the GHGIs submitted in 2009 and in 2017. Harvested Wood Products are assumed to come predominantly from "Forest land remaining forest land".

A large number of developing countries do not have repeated national forest inventories and, thus, while most of them report on deforestation (forest to non-forest transition), many do not have full information to report on the forest land category (GHG fluxes in "forest remaining forest" that is considered part of "managed lands") or forest regrowth (non-forest to forest). Many also do not have sufficient information to report on certain carbon pools (e.g. deadwood, litter and soil) or on non-CO_2 GHG (i.e., N_2O and CH_4, largely from fire). In some instances, such omissions may be relevant[14].

In recent years, developing countries' reporting included significant improvements and more wide use of the 2006 IPCC Guidelines. It appears capacities are increasing - in particular, in relation to estimation of forest-related GHG fluxes, largely due to efforts made in the context of REDD+, as indicated by the increasing number of developing countries reporting to the UNFCCC (see Fig SI 2). Submissions of REDD+ reference levels[5] (since 2014) represent the most recent data available in forest countries and illustrate that, while reporting on deforestation has improved, there are still gaps in the reporting of "Forest land", non-biomass pools, and non-CO_2 gases[15]. Despite the limitations above (which apply mainly to small and medium-sized developing countries), in this study we managed to collect information on the recent forest sink for 50 developing countries, including the most important ones in terms of forest sink and area, using the latest available information from BURs, NCs, NDCs and

REDD+ submissions. The developing countries included in our study collectively represent 66% of the FAO-FRA's "secondary forest" area from developing countries (see Methods - at global level, including developed countries, this figure increases to 80%)

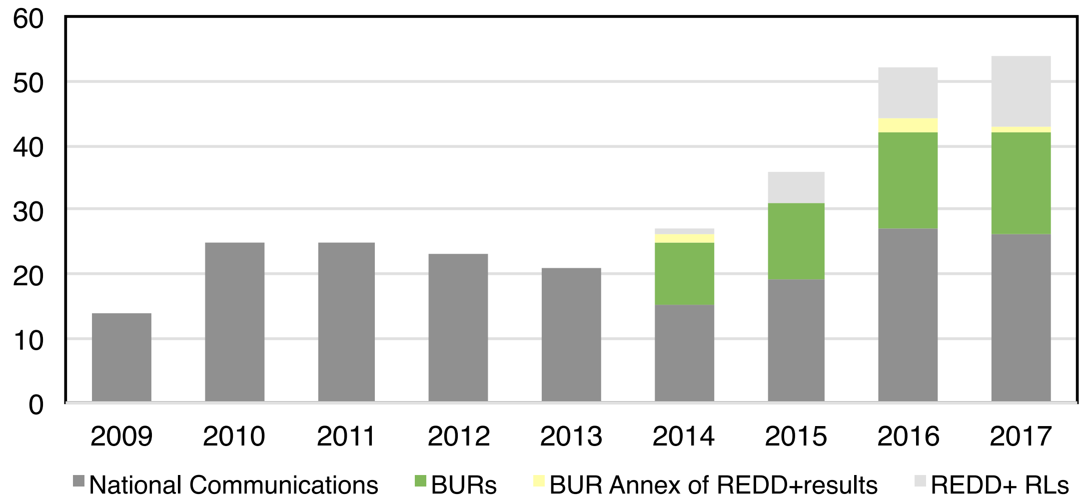

Figure SI 2 Number of UNFCCC non-Annex I countries reporting GHG estimates to UNFCCC (updated from ref.[16]).

Under Article 13 of the Paris Agreement (PA)[17] the common Enhanced Transparency Framework envisages requirements for all countries when reporting national anthropogenic GHG emissions and removals, while providing flexibility to those developing country Parties that lack capacities. Implementing this Enhanced Transparency Framework will require unprecedented efforts in estimation and reporting of GHG fluxes by all countries, including common and improved methods, capacity building and comparison with independent scientific estimates. To support this effort, the IPCC was requested to prepare a Refinement to the 2006 IPCC Methodological Guidelines, due in 2019.

1b) <u>Accounting of emissions and removals in the land-use sector</u>

Within the UNFCCC, a distinction is made between national GHG "reporting" and GHG "accounting". The former relates to information on estimates of national GHG emissions and removals that are reported through NCs, national GHGIs (as also reported in NCs), and BRs or BURs. The reported GHG estimates should in principle reflect "what the atmosphere sees" in managed lands, within the limits given by the method used and the data available. In contrast, in the context of mitigation targets (e.g. under the Kyoto Protocol and the Paris Agreement), accounting refers to the comparison of emissions and removals with a target. For instance, comparing emissions in a specific accounting period to emissions in a particular historic year or reference period (e.g. 1990), or to emission expected under a business-as-usual reference level. For the LULUCF sector, the accounting is done through policy-agreed "accounting rules", which filter the reported estimates with the aim to better quantify the results of mitigation actions[18]. Under the Kyoto Protocol, such targets were known as the Quantified Emission Limitation or Reduction Objectives (QELROs). Under the Paris

Agreement, Article 4, states that “Parties shall account for their Nationally Determined Contributions (NDC)”, with widely differing accounting rules applied so far by each country[20]. Under REDD+, results may be quantified against a “forest reference emission level or forest reference level” (FREL/FRL), including reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks.

There are unique characteristics of the land sector that have led to special consideration of how it is accounted compared to other sectors such as energy, and why it may “filter” out reported emissions and removals. These recognize that the land is both a source and sink due to natural effects as well as anthropogenic, including indirect effects and natural disturbance[20]. For example, under the Kyoto Protocol, provisions were agreed to discount the emissions due to “natural disturbances beyond the human control” (Decision 2/CMP.7, UNFCCC 2011) that may occur on managed lands (so that, under specific conditions, countries are not debited for emissions due to wildfires or disease, or credited for regrowth after natural disturbance). Other land sector issues include legacy effects, non-permanence and complexities of estimation[20]. Such features of the land sector have led to additional, unique accounting provisions in the Kyoto Protocol[7], e.g. for baseline setting (in particular, for forest management) that is intended to more directly reflect the impacts of mitigation actions.

While both GHGI “reporting” and NDC “accounting” should aim at including all significant anthropogenic emissions and removals (or justify why there are omissions), in practice this may not always occur. Reasons for omissions include data and capacity limitations or a country may only have included in their NDC those categories in which they expect to take mitigation actions. Similarly, while REDD+ aims to include significant forest fluxes, this also does not always occur in practice (see Table SI 3, Ref[15]).

The scope of coverage typically narrows — in large part due to the different purposes — as countries move from GHGI reporting to accounting (i.e. reporting tends to have the most comprehensive coverage), and further when accounting for REDD+ results-based payments in specific categories. Fig. SI 3 depicts this “funneling” effect.

Table SI 3. Scope, purpose and limitations of GHG reporting and accounting under UNFCCC.

		Scope	Purpose	Limitations
UNFCCC Reporting	**GHGI**	Anthropogenic emissions and removals	To provide a national (and global aggregate) overview of economy-wide GHG emissions and removals; estimates should allow an assessment of the total effect of mitigation measures taken by Parties.	National capacities and data availability.
UNFCCC Accounting	**Kyoto Protocol (KP)**	Anthropogenic emissions and removals	Supplementary information within the GHGI is reported to assess the implementation, or fulfillment, of commitments by UNFCCC Annex I Parties to the Kyoto Protocol. Specific accounting rules were agreed for the 1st and the 2nd Commitment Periods (2008-2012 and 2013-2020, respectively[7,8,19].	National capacities and data availability. Both may be addressed by implementing the conservativeness principle in accounting.
	NDCs (Paris Agreement)	Anthropogenic emissions and removals	To provide clear understanding of climate change *action* by countries in the context of the PA, build mutual trust and confidence, and promote effective implementation.	In addition to limitations above for GHGIs, many NDCs do not provide clarity as to the comprehensiveness of their coverage and to the accounting methods that will be used for the land sector[20].
	REDD+	Significant anthropogenic forest-related emissions and removals	To provide understanding of climate change actions in the forest sector. Most submissions state that the FREL/FRL (Forest Reference Emission Level/Forest Reference Level) is "in the context of accessing results-based payments"; REDD+ only applies to developing countries.	Countries often choose only the most significant emissions (e.g. from deforestation, excluding degradation, regrowth); currently not all are national in coverage.

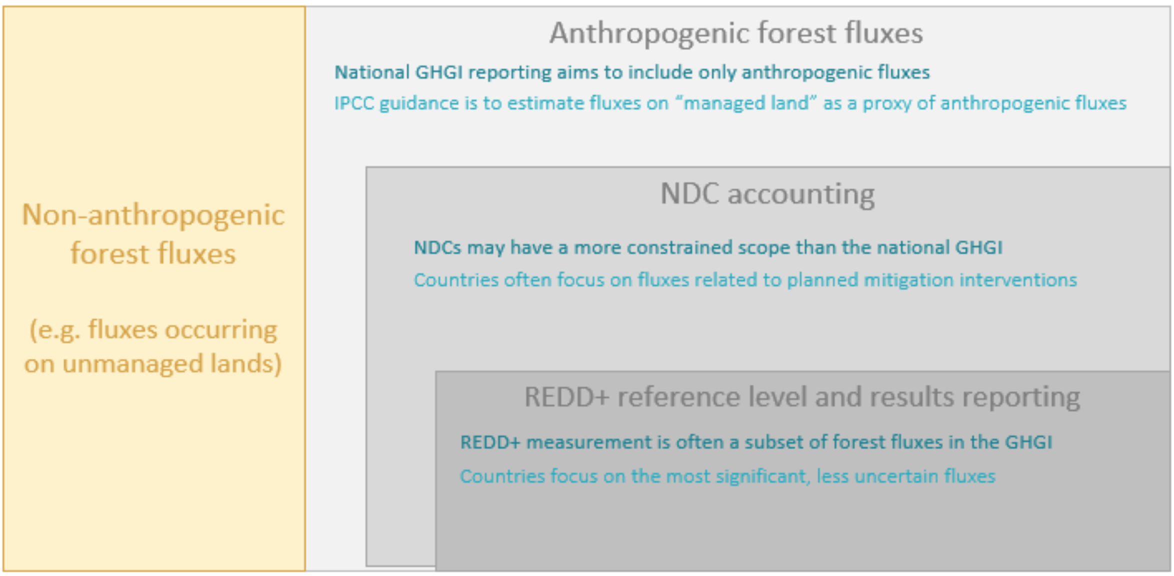

Figure SI 3. Illustration of the "funneling" effect that may occur when moving from GHGI reporting to NDC and REDD+ accounting (adapted from Ref[15])

1c) Review process of GHG Inventories

Under the UNFCCC the GHG inventories of Annex I countries are subject to a dedicated, thorough review process (Decision 24/CP.19[21]) to support the quality of national GHGIs and ensure transparency of information reported. Also, the institutional arrangements behind the national GHG inventory, which are required to ensure that all data needed are collected and compiled and that GHG estimates are timely, are subject to review. The review process aims to ensure that the Conference of the Party (COP) is provided with the best information available for assessing the overall effects of measures taken (by Annex I Parties) as well as their cumulative impacts and the extent to which progress towards the objective of the UNFCCC is being achieved.

By contrast, GHG inventories of Non-Annex I countries do not undergo a similar review process, although they are subject to an international consultation and analysis (ICA) that assesses the completeness of information provided and its transparency (Decision 2/CP.17[22], and 20/CP.19[23]). The ICA neither investigates the accuracy and quality of information provided nor provides guidance on how to enhance it, although experts may indicate areas where capacity of the reporting country needs to be enhanced. On the other hand, accuracy of information submitted for REDD+ is within the scope of the technical assessment process.

The Enhanced Transparency Framework under the PA it is expected to develop a common framework for both reporting and review of national GHGIs, which takes into account capacity and capabilities of countries as well as the significance of sources and sinks. Checking the quality of reported information and providing guidance on how to enhance it will likely be the fundamental objectives of such a common framework, to ensure that the information reported under the PA is credible and the assessment of progress towards the PA's mitigation goal is effective.

Overall, the review process has led so far to significant improvements in the quality of GHGIs, for both developed and developing countries. The extent to which this trend will continue under the Paris Agreement will largely depend on the modalities of the Enhanced Transparency Framework, still under negotiation.

2. Country GHG data for 2005-2014

This section presents country data on forest area and forest CO_2 emissions and removals (averages for the period 2005-2014) for the developed (Annex I) countries and the developing (Non-Annex-I) countries analysed in this study.

2a) Annex I ("developed") countries

Table SI 4. Developed country data on forest area and forest CO_2 emissions and removals (average of yearly values for the period 2005-2014).

	Forest area (Mha)	Emissions (+) or removals (-) (Mt CO_2/y) *	IPCC methodological guideline	Source
Australia	138	-43	2006 Guidelines[6]	GHGIs 2018[24]
Belarus	8	-38		
Canada	226	-29		
EU (28 countries)	162	-485		
Japan	25	-79		
Kazakhstan	13	-11		
New Zealand	10	-38		
Norway	12	-31		
Russia	672	-700		
Switzerland	1	-2		
Turkey	22	-50		
Ukraine	11	-62		
USA	291	-738		
Total	**1591**	**-2306**		

* From the "Forest land" category (including "forest remaining forest" and "land converted to forest", and excluding deforestation), Harvested Wood Products and forest fires from GHGIs 2018[24]. The totals in this table correspond to the left columns of Figs 5a and 5b (main text).

2b) Non-Annex I ("developing") countries

Table SI 5. Developing country data on forest area and forest CO_2 emissions and removals (average of estimates available the period 2005-2014).

	Forest area (Mha)	Emissions (+) or removals (-) (Mt CO_2/y)*	IPCC methodological guideline	Source*	Comments*
Argentina	27	-4	2006	BUR2 (2017)	Value for 2014. Area taken FAO-FRA 2015
Brazil	235	-337	2003/2006	NC3 (2016)	Based on tab 3.110 of NC3 for years from 2005 to 2010
Chile	12	-3	2006	REDD+ (2016)	Based on estimates for the REDD+ activities FD, C, ECS for years from 2005 to 2013
China	200	-510	96/2006	BUR1 (2017)	Value for the years 2005 and 2012 as elaborated by Ref.[16]
Colombia	51	23	2006	NC3 (2017)	Based on estimates for years from 2005 to 2012
Congo	15	16	2006	REDD+ (2016)	Based on estimates for the REDD+ activity FD for years from 2005 to 2012
Costa Rica	1	-2	2006	REDD+ (2016)	Based on estimates for the REDD+ activity ECS for years from 2005 to 2014. Area from FAO-FRA (2015)
Ecuador	13	-15	2003/2006	NC3 (2017)	Value for the years 2006, 2010 and 2012
Ethiopia	13	-5	2006	REDD+ (2016)	Based on estimates for the REDD+ activity ECS For years from 2005 to 2013. Area from FAO-FRA (2015)
Georgia	3	-6	96/2003/2006	NC3 (2016)	Based on estimates for years from 2005 to 2011
Ghana	9	7	2006	REDD+ (2017)	Based on estimates for the REDD+ activities FD, ECS, for years from 2005 to 2014.
India	69	-50	2003	REDD+ (2018)	Based on estimates for the REDD+ activity SMF for years from 2005 to 2008. Note that BUR1 (2016) reports a greater sink for forest land (-200 $MtCO_2$/y) in 2010
Indonesia	88	-14	2006	NC3 (2018)	Based on estimates for years from 2005 to 2014. Excludes peat fires and peatland decomposition
Kenya	4	15	1996 / 2003	NC2 (2015)	Based on estimates for years from 2005 and 2010
Lao	17	-8	2006	REDD+ (2018)	Based on estimates for the REDD+ activities FD, ECS for years from 2005 to 2014. Area from FAO-FRA 2015
Malaysia	18	-226	2006	REDD+ (2015)	Based on estimates for the REDD+ activities SMF, C for years from 2005 to 2014.
Mexico	33	-163	2003	BUR1 (2015)	Value for the year 2011. Area from FAO-FRA 2015
Mongolia	13	4	2006	REDD+ (2018)	Note that different values are reported in the NC3 (2018).
Namibia	7	-29	2006	BUR2 (2016)	Based on estimates for years from 2006, 2008, 2010, 2011 and 2012
Papua New Guinea	13	23	2006	REDD+ (2017)	Based on estimates for the REDD+ activities FD, ECS for years from 2005 to 2013. Area from FAO-FRA 2015.
Paraguay	15	-21	2003	NC3 (2017)	Value for 2010 and 2011. Note that BUR 1 (2015) reports a much smaller sink for forest land (-21 $MtCO_2$/y) for 2011
Rep. Korea	6	-59	1996/2006	BUR1 (2014)	Based on estimates for years from 2005 to 2012
S. Africa	23	-34	2006	BUR2/ NIR (2018)	Based on estimates for years from 2005 to 2010
Swaziland	1	-5	2003	NC3 (2016)	Value for 2010
Tunisia	1	-6	2006	NC2 (2014)	Value for 2010
Uruguay	1	-4	2006	NC4 (2017)	Value for 2013
Venezuela	47	-90	2006	NC2 (2018)	Value for 2010
Viet Nam	14	-40	96/2003	BUR2 (2017)	Value for years 2010 and 2013
Sub-total	*954*	*-1540*			
Other countries	*44*	*-40*			
Total	**999**	**-1580**			

* Including (partly or fully) afforestation, regrowth and forest degradation, but excluding emissions from deforestation, peat fires and peat decomposition. We used only recent (post-2014) information from REDD+ submissions[5] (i.e., forest degradation (FD), conservation (C), sustainable management of forests (SMF) and enhancement of forest carbon stocks (ECS), which we considered all being part of the "forest land" category), complemented by BURs[4] and NCs[3] ("forest land" category). Where specified, area is taken from FAO-FRA 2015[25] ("secondary" and "planted" forests). The totals in this table correspond to the central columns of Figs 5a and 5b (main text).

3. How anthropogenic effects (direct and indirect human-induced) are captured by GHG inventories and by Houghton's model

The approach of GHGIs to fully capture the forest carbon stock changes, and the associated emissions and removals caused by both direct and indirect human-induced drivers, requires periodic data collection of two types of data: the activity data (i.e., land area converted to or from forest, managed forest area); and emissions factors (i.e., net emissions per unit of area, which may be function of yield tables - expressing the growth of forest species in certain conditions - and other parameters). The use of activity data and emissions factors based on historical data not subject to a continuous or periodical update would result in not capturing, or only partially capturing, the actual effects of direct and indirect human-induced drivers.

The degree to which anthropogenic effects are captured stems from the quality and timelines of data used for preparing estimates. The possibility to disaggregate the impact of different drivers depends on the methodology applied. Two substantially different methodological approaches are described by the IPCC for preparing national GHG estimates for forest: the "stock-difference" and the "gain-loss" methods.

The "stock difference" method allows for the calculation of net emission/removal by using the difference in carbon stocks on land between two points in time. All direct, indirect and natural drivers and effects are in principle fully captured and cannot be disaggregated.

The "gain-loss" method estimates separately all the components of the carbon balance of a land, so that a disaggregation among various drivers of emissions and removals may be performed, e.g. disaggregating harvesting losses from natural disturbance losses, and post-harvesting gains from post-disturbance gains. On the contrary, the stock difference is not able to discriminate among drivers. However, separating the effects of direct human-induced drivers from those of indirect human-induced drivers remains a challenge that cannot be addressed operationally with current methodological approaches. A gain-loss approach utilising constant emissions factors will implicitly capture indirect effects prevalent at the time of data collections for the emissions factors, but not the transient effects over time. By contrast, gain-loss methods that utilise climate sensitive growth and mortality models, or climate sensitive models of dead and soil organic matter dynamics will capture transient indirect anthropogenic effects. The methods applied in selected national GHGIs are summarized in Tab. SI 4.

Table SI 6. Methods used to estimate forest CO_2 fluxes in GHGIs of the main countries analysed in this study, and implications for the inclusion of indirect effects.

	Overview of the methods (based on NIRs[2] for Australia, Canada, EU, Russia and USA, on NC[3] for Brazil, and BURs[4] of China and India)	**Are transient effects of environmental change (indirect human effects) included in the estimate reported in the GHGI ?**
Australia	Australia uses different methods for different subdivisions of its forest land. Gain and loss method for the subdivision "harvested natural forest" is modeled by using age-related net increment rates, constant across the time series. Process models (based on empirical tree yield formula that allows for responses to climatic variability, while empirical data and parameters constrain initial aboveground biomass and forest growth) are applied to forest plantations and to other native forest, including their conversion (deforestation and afforestation). As all methods are based on yield curves they capture indirect effects only for the period of data collection.	Mostly not
Canada	Gain-loss method using annual statistics of forest management, natural disturbances, and land-use changes, based on empirical data of forest growth and mortality and simulated C dynamics of dead organic matter and soil C pools. Data integrated with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3[24]). Empirical yield curves quantify age, species, and site-class forest growth rates but these do not vary over time. Indirect effects are only transiently captured to the extent to which they are reflected in the sample plot data from which yield curves were constructed.	Mostly not. Only climate change impacts on disturbances are captured. Impacts on forest growth, non-disturbance mortality and dead organic matter and soil C are not captured.
EU	In the EU, 17 countries use the gain-loss method and 11 countries use the stock-difference method. Most countries using the gains-loss method estimate the increment using information from national forest inventories repeated over time, which means that the transient impact of recent indirect effects may be assumed to be largely reflected in the GHG estimates. By contrast, few countries (e.g. Italy, Luxembourg, Romania and UK) use a single yield curve to estimate the gains for the entire time series, which means that the transient impact of recent indirect effects is mostly not captured in GHG estimates.	Mostly yes
Russia	A gain-loss model is applied to the different age classes of the prevailing species for estimating emissions and removals from the managed forest. The model includes gain from increment, loss from harvesting, loss from forest fire and loss from drainage of organic soils. Calculations are done on the basis of annual forest resource assessments (including forest management plans and official information on disturbances) on growing stocks by species and age class, repeated over time. Thus, in theory, these calculations incorporate the impacts of CO_2 fertilization, N deposition and temperature regime. However, given many field data used to estimate forest growth are not very recent (V. Korotkov, personal communication), we assume that indirect effects are only partly captured in the GHGI.	Partly yes
USA	Stock-change method based on extensive network of permanent forest sample plots maintained by the US Forest Service, updated periodically, therefore capturing transient effects. However, natural disturbances are captured with some delay because of the sampling system used.	Mostly Yes
Brazil	Brazil explicitly applies the IPCC's managed land proxy and separates managed forest land (235 Mha, including "managed forest", "secondary forest" and "reforestation") from unmanaged forest land (258 Mha). However, the managed land area includes around 206 Mha of areas in which "human action did not cause significant alterations in its original structure and composition". In this area, a net sink of around 1.6 tCO_2 /ha has been reported according to information collected in field plots of scientific studies, mainly in the Amazon region. This net sink is therefore due to the indirect effects of human-actions. Source: 3rd NC (2016), tables 3.81-3.110	Mostly Yes
China	For estimating emissions and removals in forest land remaining forest land (i.e. changes in forest and other woody biomass stocks), a combination of gain-loss methods and stock-change methods is used, depending on the forest type[16], based on carbon stock changes in forests over time from repeated National Forest Inventories.	Mostly Yes
India	Carbon stock changes in forests over time, from repeated National Forest Inventories, therefore capturing transient effects.	Mostly Yes

For developed countries, we estimate that the transient impact of recent indirect effects on CO_2 fluxes are partly or mostly captured in country GHGIs corresponding to about 87% of the total forest net CO_2 flux and to 74% of the total managed forest area reported. Due to lack of precise methodological information, it is difficult to provide similar estimates for most developing countries. Nevertheless, based on the available information (Tab. SI 4) we conclude that the GHGIs of the most important developing countries in terms of forest CO_2 fluxes (i.e. at least China, Brazil, India, and also Malaysia, accounting for two thirds of the forest sink of developing countries in Fig. 5a) capture most or all recent indirect anthropogenic effects.

The Houghton bookkeeping approach of calculating the CO_2 flux similarly uses activity data (e.g., land cover change, wood harvest rates) and then uses rates of growth and decay and carbon density data that are fixed, taken from field data collected over a certain period (1970–2010). This approach implicitly captures the impacts of environmental changes that are expressed in the data during that period, similarly to a gain-loss approach with constant emissions factors. However, because these fixed rates and values are then applied throughout a much longer simulation period, during which the time-varying impacts of environmental change would be expected to be greater, the approach potentially overestimates past effects and underestimates recent and future effects.

The main conceptual differences between Houghton's bookkeeping model[25,26] and those country GHGIs that reflect indirect effects are further illustrated in Fig. SI 4. The first difference relates to the impact of indirect effects over time. The bookkeeping model assumes that each subsequent harvest and regrowth cycle results in the same carbon stock in mature forests (Fig. SI 4a), and that carbon stock does not increase further in existing forests once these have reached a maturity level established by the model and are not harvested anymore (Fig. SI 4b). The average biomass densities used in the model are based on relatively recent (1970–2010) observations and thus implicitly include impacts of environmental changes up to that date, but not beyond. By contrast, those GHGIs which include the transient impact of indirect effects on all carbon stock changes occurring in "managed" forests, including growth enhancements due to recent environmental changes, typically see increases of carbon stocks at maturity. This is consistent with independent field data, which show a gain in carbon in mature forests (e.g., ref[27]).

The second key difference relates to the area considered as managed forest. While Houghton's bookkeeping model considers "secondary" forest as the area of land experiencing specific management activities (i.e., afforestation, reforestation, wood harvest and regrowth), the GHGIs' "managed land" concept is broader and may also include lands subject to fire suppression and activities related to the social and ecological functions of land (such as protection of parks). Overall, the differences above (i.e. that most GHGIs include partly or fully the impact of recent indirect effects, and consider a larger forest area) explain the mostly lower sink in forests generally reported by ref[26] compared to GHGIs (Fig. 4a in main text, Fig. SI 6), and to some extent also the different trends (see EU and Russia, Fig. SI 6, Fig. SI 7).

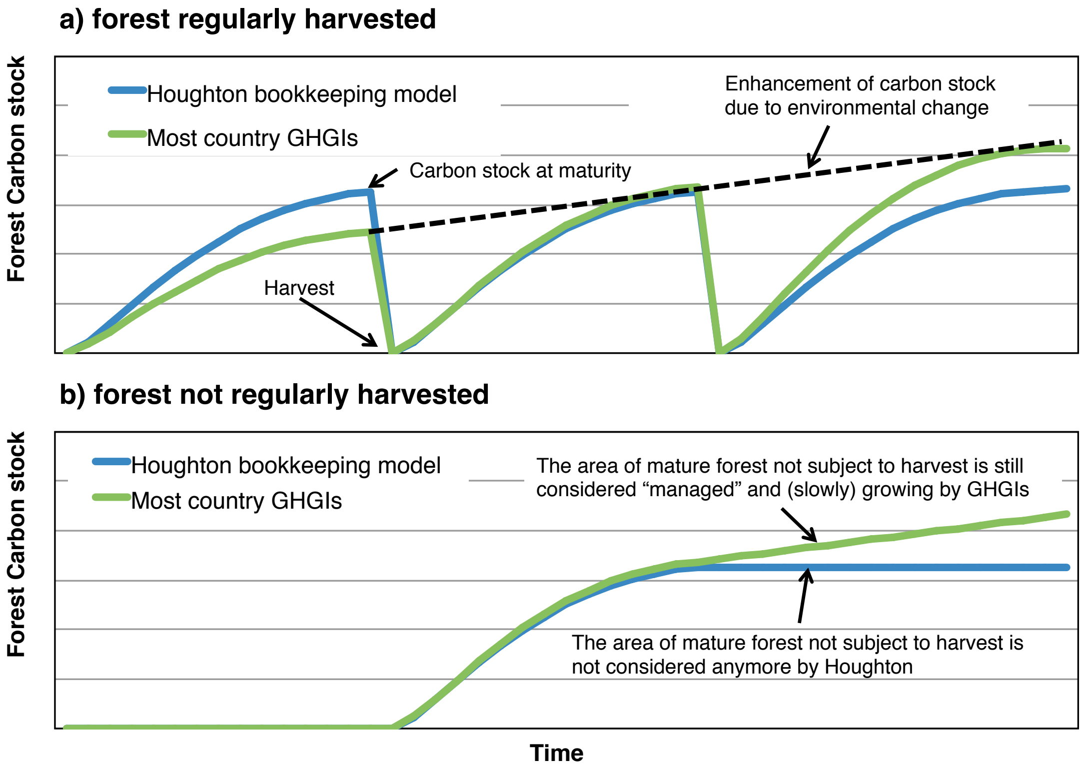

Figure SI 4. Conceptual differences between the Houghton's bookkeeping model[26] and those country GHGIs that reflect transient indirect effects (i.e. environmental changes) on the estimated dynamics of stand level carbon stock: (a) in a managed forest subject to regular harvest, and (b) not regularly harvested. While the impact of environmental change on the carbon stocks is historically mostly positive, in some countries it can lead to declining carbon stocks.

4. Characteristics of the DGVMs

Table SI 7. Relevant characteristics of the dynamic global vegetation models used in this study.

Model name	Spatial resolution	Fire simulation and/or suppression	Wood harvest and forest degradation	Climate and variability and CO_2 fertilization	Carbon-nitrogen interactions, including N deposition	Source
JSBACH	1.875°x1.875°	Yes	Yes	Yes	No	[30]
ORCHIDEE	0.5°x0.5°	No	No	Yes	No	[31]
VISIT	0.5°x0.5°	Yes	Yes	Yes	No	[32]
OCN	0.5°x0.5°	No	Yes	Yes	Yes	[33]
JULES	1.875°x1.6°	No	No	Yes	No	[34]
CLM4.5	1.25°x0.9375°	Yes	Yes	Yes	Yes	[35]
LPJ-GUESS	0.5°x0.5°	Yes	No	Yes	No	[36]
LPJmL	0.5°x0.5°	Yes	No	Yes	No	[37]
ISAM	0.5°x0.5°	No	Yes	Yes	Yes	[38]

Information based on ref[39].

5. Additional results from DGVMs

4a) Forest net CO_2 fluxes by each Dynamic Global Vegetation Models (DGVMs), in primary and secondary forest

Table SI 8. Global forest net CO_2 fluxes for secondary and primary forest area in the period 2005-2014, as estimated in this study from nine DGVMs.

	Forest net flux (Mt CO_2/y, averages for the period 2005-2014)[1] excluding deforestation	
	secondary forest	**primary forest**
JSBACH	-1554	-3122
Orchidee	-2499	-3821
VISIT	-3690	-5164
OCN	-3591	-4470
JULES	-2946	-3509
CLM4.5	-2357	-5681
LPJ-GUESS	-2780	-4135
LPJmL	-2558	-4554
ISAM	-1707	-4047
Average	**-2631**	**-4278**
1 SD (+/-)	*731*	*797*

[1]To separate the primary and secondary forest net flux in DGVMs we used the fraction of primary and secondary forest area from LUH2-v2h (see Methods).

The range of CO_2 estimates in secondary forest among the nine DGVMs included in our study is high (Table SI 8), but broadly comparable to the one found in a recent study in presenting DGVM results[40].

While in the period 2005-2014 the forest sink in secondary forest is of similar magnitude in developed countries (≈-1.3 $GtCO_2$/y or ≈-1.0 tCO_2/y/ha) and in developing countries (≈-1.4 $GtCO_2$/y or ≈-1.4 tCO_2/y/ha), the sink of primary forest is greater in developing countries (≈-3.1 $GtCO_2$/y, or ≈-2.0 tCO_2/y/ha) than in developed ones (≈-1.1 $GtCO_2$/y or ≈-1.0 tCO_2/y/ha). The greater impact of indirect effects (in particular CO_2 fertiliztion) per unit area in developing countries, and especially in primary forests (typically tropical humid forests with high productivity), is consistent with other studies[41,42].

4b) Long-term forest net CO_2 fluxes by DGVMs

The long-term trend in CO_2 flux is consistent accross the nine DGVMs included in our study, with all models indicating an increasing CO_2 sink due to the impact of environmental change ("indirect effects"), both in secondary forests (Fig. SI 5) and in primary forests.

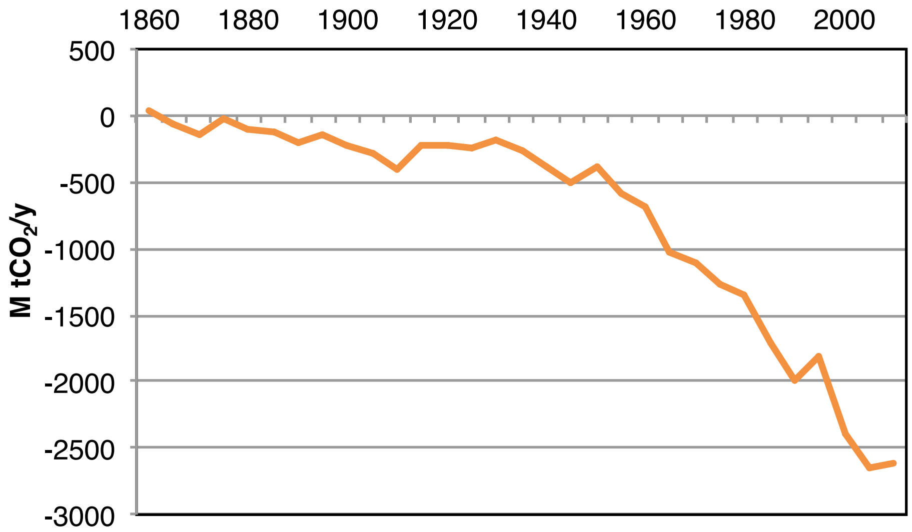

Figure SI 5. Trend of global forest CO_2 fluxes in secondary forests associated with indirect effects only (environmental change), as estimated in this study in the period 1860-2014 (average of nine DGVMs).

6. Country case studies

In this section, we first (a) illustrate a comparison of selected developed country GHGIs vs. another relevant global-level assessment[43]. We then show the same analysis done in the main text (bookkeeping model and DGVMS vs. GHGIs, Figs. 4 and 5) for (b) selected developed countries/regions (EU, Russia and USA, Fig. SI 6, with further insights in Fig. SI 7) and for (c) selected developing countries (Brazil and China, Fig. SI 8). The cases studies in (b) and and (c) represent the six most important countries/regions in terms of net forest CO_2 flux, collectively representing 72% of the global forest sink reported by countries and included in Fig. 5 (main text) for the period 2005-2014.

5a) Annex I (developed) countries: GHGIs vs. other studies

Table SI 9 compares the net forest CO_2 fluxes from the main developed country GHGIs with results from Pan et al.[43], i.e. one of the most comprehensive recent studies on global carbon budget with country-level details. When all pools are considered, ref.[43], estimates a sink that is more than twice that reported by all developed country GHGIs. For living biomass, GHGIs report similar sink values than ref[43], especially when differences in forest areas are taken into account (Tab SI 9, last column). However, for the other carbon pools (dead organic matter, soil, harvested wood products) the difference is striking, especially for soil: most country GHGIs provide an estimate for these pools (see Fig. SI 1), but the estimated sink is generally small (about 20% of the total net forest sink of developed countries), while ref.[43] estimate a much larger sink (55% of the total net forest sink). Given that non-biomass pools, and soil in particular, are the most uncertain component of the forest flux (with most estimates derived from empirical models and simple extrapolations rather than from direct measurements[43]), the GHGIs' estimates may be considered "conservative".

Table SI 9. Net forest CO_2 flux in biomass and non-biomass pools and forest area from GHGIs and from Pan et al.

	All pools		**Living Biomass**		**Non-living biomass pools** (3)		**Forest area**	
	GHGIs	**Pan et al.**	**GHGIs**	**Pan et al.**	**GHGIs**	**Pan et al.**	**GHGIs**	**Pan et al.**
	Mt CO_2/y for the period 2000-2007(1), excluding deforestation						(Mha)	
Europe (2)	-609	-975	-503	-579	-106	-396	195	202
Russia	-633	-1698	-596	-561	-37	-1137	637	834
USA	-728	-876	-443	-539	-285	-337	290	254
Total Annex I	**-2320**	**-4613**	**-1750**	**-2061**	**-570**	**-2552**	**1551**	**1723**

(1) This period is selected because it is used by Pan et al. 2011

(2) Including 28 countries under the EU plus other 13 countries reported under "Europe" by Pan et al. 2011

(3) Including dead organic matter, soil, harvested wood products.

A comparison between GHGIs and other forest GHG emission datasets, including FAO and Global Forest Watch, has been made by ref.[16].

5b) Annex I (developed) countries: bookkeeping model, DGVMs, GHGIs

The same approach of comparing the forest net GHG fluxes from various sources illustrated in the main text (Fig. 4) is presented here for selected cases (EU, Russia and USA, Fig. SI 6, with an analysis of the main drivers in Fig. SI 7). These cases represent the main contributors to the total forest net CO_2 flux in developed countries' GHGIs (i.e. UNFCCC Annex I), with EU contributing 22%, Russia 24% and US 36% (collectively 82%) for the period 1990-2014. In terms of area, these three cases represent 70% of the "managed" forest area reported by developed countries. We assume here that the majority of CO_2 fluxes reported in the GHGIs of these three cases include the transient impact of indirect effects (Table SI 6).

A general explanation for the lower sink reported by Houghton's bookkeeping model compared to GHGIs (Fig. SI 6a) due to indirect effects is illustrated in Fig. SI 4, with further differences due to managed forest area.

When estimates from the bookkeeping model and estimates of the indirect effects obtained from DGVMs are aggregated, the resulting total forest fluxes generally move much closer to those reported by GHGIs (grey column vs. green column in Fig. SI 6a), also when expressed on an area basis (Fig. SI 6c). Although this match is remarkable, and certainly points to the importance of reconciling differences related to the impact of indirect effects and of different areas considered "managed", it would be erroneous to conclude that these two factors alone explain all the differences between the datasets analyzed here. There are a number of additional factors and methodological complexities that are not entirely considered in the paper.

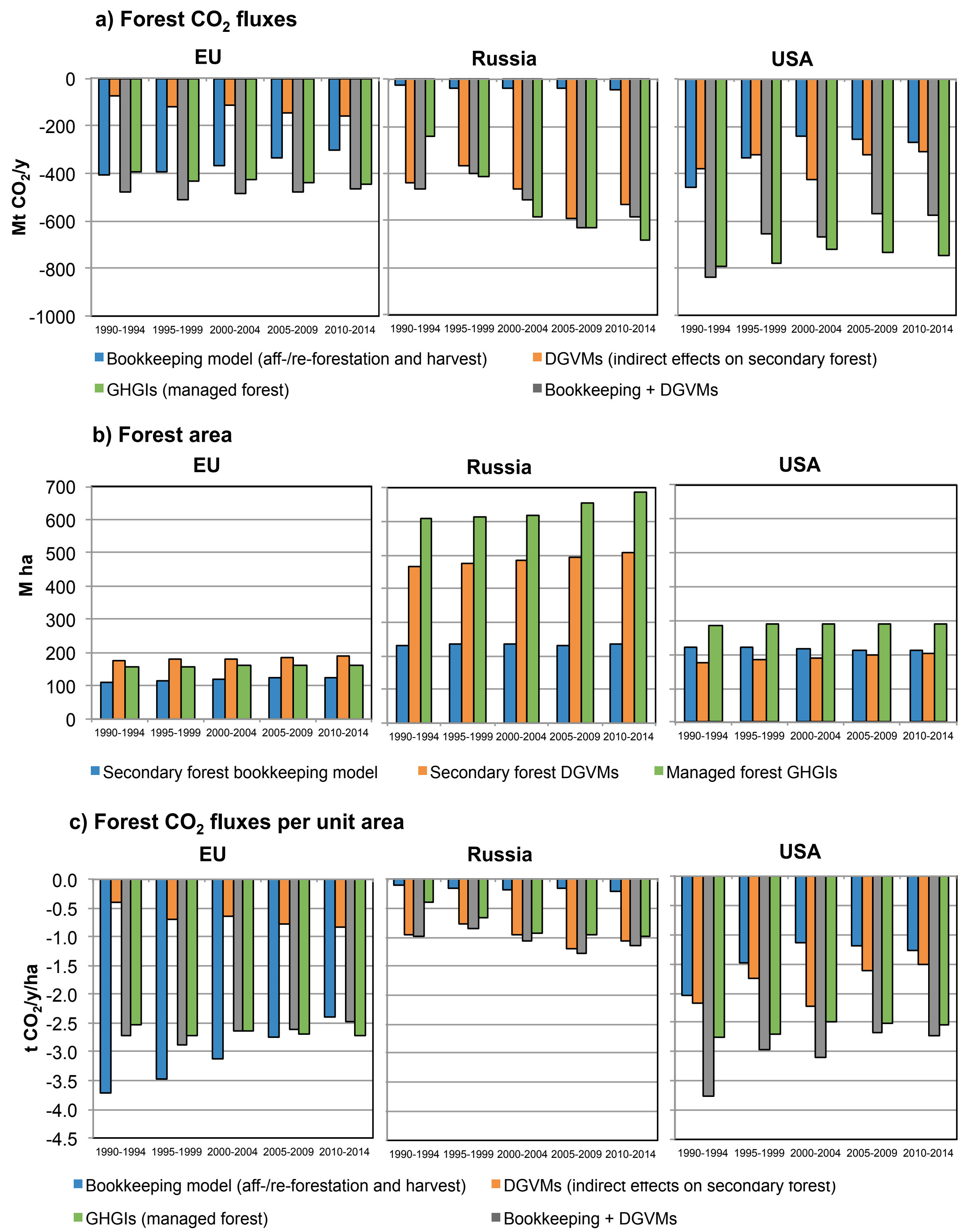

Figure SI 6. Comparison and reconciliation of developed countries' forest CO_2 between global models and countries' GHG inventories for EU, Russia and the USA. Forest net CO_2 flux estimates (a), forest area (b) and forest net CO_2 fluxes per unit area (c). From Houghton's bookkeeping model[28], the DGVMs used in this study and country 2017 GHGIs. See Fig. 4 (main text) for further details.

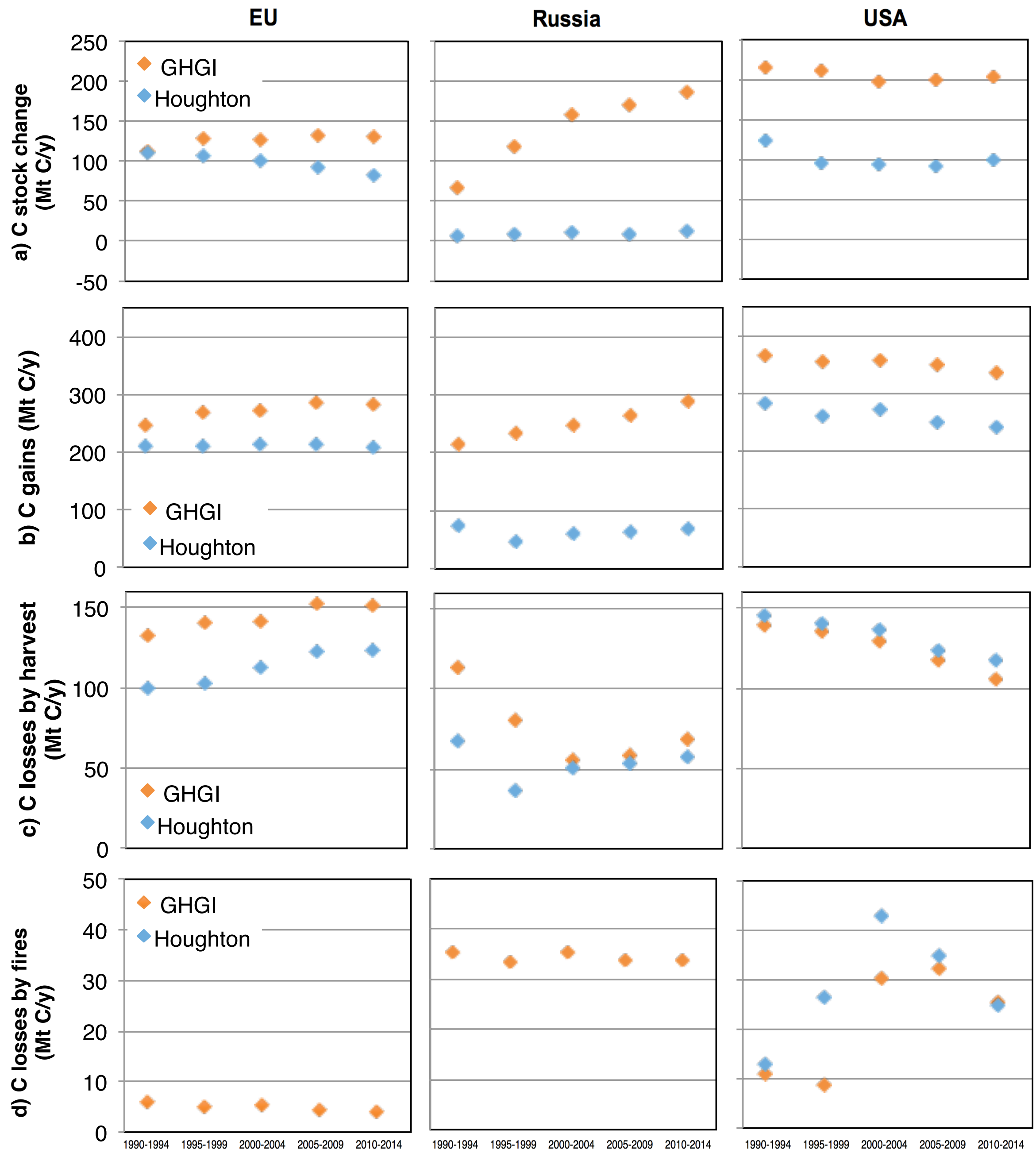

Figure SI 7. Disaggregation of various components potentially contributing to the difference between 2017 GHGIs (in EU, Russia and USA) and Houghton's bookkeeping model[28]. Carbon stock changes (a), carbon gains (b), carbon losses by harvest (c), carbon losses fires (d). Note that ref.[28] do not report fire losses for the EU and Russia. The carbon stock change corresponds to the net sink shown in Fig SI 6a (with opposite sign, and divided by 44*12 to convert from CO_2 to C). Harvest data come from country statistics, fires from the GHGIs. The gross carbon gain is estimated as: C stock change + harvest + fires.

To gain insight into possible additional factors involved, Fig. SI 7 illustrates - for both GHGIs and Houghton's bookkeeping model, and for EU, Russia and USA - a crude disaggregation into two main categories of factors affecting the carbon stock change (i.e., the net forest carbon flux), expressed in carbon: "gains" (i.e., net increment) and "losses" (i.e., harvest and fires). It appears that it is mainly the carbon "gains" (Fig. SI 7b), and not the harvest (Fig SI 7c), that explain the differences in carbon stock change between GHGIs and Houghton. For EU and Russia, while the absolute difference in carbon "gains" between GHGIs and Houghton (Fig. SI 7c) is partly explainable by the differences in area (Fig. SI 6b) and partly by fires (included in GHGIs but not in Houghton), the fact that this difference increases over time (also when estimates are expressed on an area basis) deserves further attention. This is likely due to the fact that, while estimates in Houghton's bookkeeping model do not include the impact of transient indirect effects, these effects may be assumed to be largely included in EU, and partly (or mostly) in Russia (table SI 6). For Russia, another factor may be harvest: the higher harvest levels in GHGIs compared to Houghton in the 1990s may have led to younger forests today, characterized by higher increment than estimated by the bookkeeping model. Irrespective of other factors potentially involved, this trend of increasing increments associated with impact of environmental change in the recent decades is consistent with results from DGVMs (for which the sink, on average, increases over time in the EU and Russia but not in USA, Fig SI 6a), and with the faster tree growth reported in the scientific literature. For instance, ref.[44] reported a faster tree growth, by 32 to 77%, measured for the dominant tree species Norway spruce and European beech in Central Europe in the last 50 years. Similar results have been reported for Finland[45]. Similarly, ref.[46] attributed to climate and CO_2 fertilization the vast majority of the positive trend in Net Ecosystem Productivity simulated in Europe between 1950 and 2000. The leveling-off in the historical increase in increment reported for Europe by ref.[47] is mainly associated to forest aging, and therefore does not contradict the (overall positive) effect of environmental change on tree growth. The much greater sink in Russian forests estimated by ref.[48] as compared to the GHGI, reflected also in ref.[43], seems to be mostly explainable by differences non-biomass pools (see SI section 6c). Given the global relevance of the carbon budget of Russian forests, addressing its large uncertainty should be seen as a priority of the global scientific community.

In the USA, the lack of trend in the difference in carbon "gains" between GHGIs (mostly including indirect effects) and the bookkeeping model (not including indirect effects) (Fig SI 7b) may be partly explained by the fact that the GHGI reflects the elevated tree mortality and stand scale disturbances in response to warming and drought, more frequent and larger fires as well as outbreaks of bark beetles observed especially in the west in the last two decades[49–51]. This may have counterbalanced any possible positive effect of indirect effects on growth (observed in EU and Russia).

Another factor could be a different treatment of specific carbon pools, such as soil or harvested wood products. Most GHGIs report on soil (Fig. SI 1), with a sink corresponding to 12% of the total forest CO_2 reported by developed countries (≈250 $MtCO_2$/y for the period 1990-2014). The soil sink in Houghton's bookkeeping model is lower (≈40 $MtCO_2$/y for the period 1990-2014, equal to 5% of the total forest CO_2 sink considered in this study). On harvested wood products, according to ref.[16] estimates for Russia and US are quite similar between GHGIs and Houghton's bookkeeping model. A disaggregation of the forest sink by different carbon pools is not available yet for DGVMs.

It should be noted that the difference in carbon gains between GHGIs and Houghton might be due to other factors not assessed here, such as natural disturbances, the different shapes of growth curves and the different forest age structures considered (implicitly or explicitly) by GHGIs and Houghton's model. These factors may explain, for example, the poor match between the Houghton's bookkeeping model and those GHGIs not including the impact of indirect effects, such as Australia and Canada (data not shown). Furthermore, where countries have a small net forest CO_2 flux (Australia and Canada together contribute to only 4% of the total net forest sink in developed countries for the period 1990-2014) the ratio between the "signal" (i.e. the forest sink) and the "noise" (other methodological factors, including natural disturbances, which are particularly relevant in Australia and Canada) is low, making our analysis more difficult. These additional factors are not discussed further and are considered outside the scope of this paper. However, it is unlikely that the possible influence of other factors would contradict the conclusions already drawn in the main text: considering that the impact of indirect effects (i.e. environmental change) and the different areas of forest considered "managed" helps to reconcile forest CO_2 estimates between global models and country GHGIs.

5c) Non-Annex I (developing) countries: bookkeeping model, DGVMs, GHGIs

Here we present a comparison of country GHGIs, the bookkeeping model and DGVMs for the most important developing countries (Brazil and China) in terms of the forest CO_2 sink reported to UNFCCC for the period 2005-2014 (see Methods). In all these cases we assume that the country GHGIs include most of the recent transient impacts of indirect effects on the forest sink (see Tab. SI 6), which are excluded from the bookkeeping model whose fixed biomass density and growth/decay rates are based on historical data. For all these countries, the difference (gap) between GHGIs and the bookkeeping model is relevant, reaching 0.8 $GtCO_2$/y for the sum of the three countries (difference between the blue and the green column in the right of Fig. SI 8a). This gap is particularly relevant for Brazil, where the bookkeeping model estimates a source (mainly due to harvest) from a small area (22 Mha), while the country reports a relevant sink from a much larger area (235 Mha, including 206 Mha of areas considered "managed" but where "human action did not cause significant alterations in its original structure and composition", see Tab. SI 6). The aggregated gap (sum of the two countries) is halved when the impacts of indirect effects modeled by DGVMs are added to estimates from the bookkeeping model (orange and grey columns in the right of Fig SI. 8a), and nearly entirely eliminated when the different areas (Fig. SI 8b) are taken into account (Fig. SI 8c). These results confirm and extend the previous preliminary analysis of ref.[16], and are entirely consistent with the analysis showed for developed countries (Fig. SI 6).

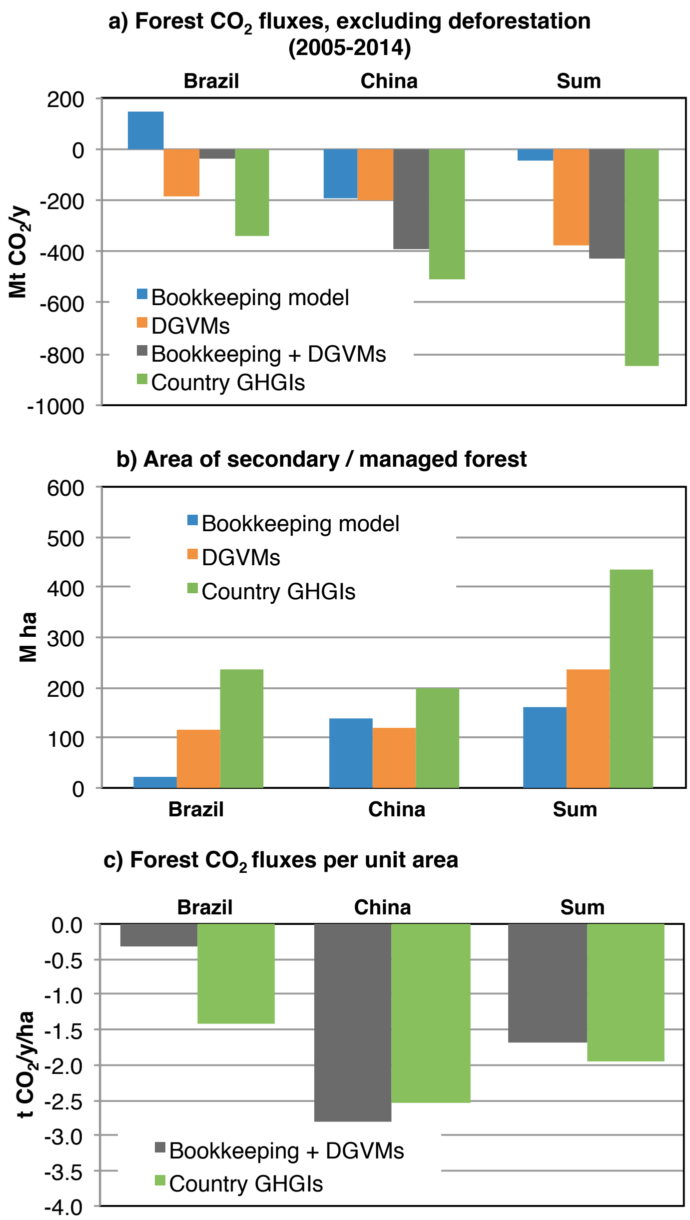

Figure SI 8. Comparison and reconciliation of developed countries' forest CO_2 between global models and countries' GHG inventories for Brazil and China. Forest net CO_2 flux estimates (a), forest area (b) and forest net CO_2 fluxes per unit area (c). From Houghton's bookkeeping model[28], the DGVMs used in this study and country GHGIs (Brazil 3rd NC3 2016 and China's BUR1 2017, as elaborated by ref.[16]), referred to the period 2005-2014. Forest fluxes include afforestation and regrowth, and exclude deforestation. See Fig. 4 (main text) for further details.

7. The proposed disaggregation of global models' results and implications for historical GHG estimates

This section summarizes how the disaggregation of the global models' results in this study improves their comparability with GHGIs. The tables below, exemplified for Annex I (developed) countries only, should be read in conjunction with Fig. 3c in the main text. The same disaggregation can be applied also in developing countries.

Table SI 10 presents the disaggregation used in IPCC AR5[52,53], which considers only two categories of land-related GHG fluxes: the net "anthropogenic" flux (the first row of Table SI 10, i.e. ref.[28], including deforestation and direct anthropogenic effects only (although some non-transient indirect effects are implicitly included), corresponding to area under the blue line in Fig 3c) and the "residual sink" (including indirect anthropogenic and natural effects, corresponding to area under the red line in Fig 3c). This disaggregation does not allow these GHG estimates to be conceptually comparable to those reported in country GHGIs (Tab SI 12, corresponding to area under the dashed green line in Fig 3c), because most GHGIs include part, or most, of the recent indirect anthropogenic effects on "managed" forests, estimated over an area which is much larger than the one used by ref.[28] (see Fig. 3c). As a result, the net sink estimated by Houghton's bookkeeping model (Table SI 10, first row) is much smaller than the one reported by GHGIs (Table SI 12, sum of first two rows).

Table SI 10. Forest-related net CO_2 flux for developed countries (UNFCCC Annex I), from the global models used in this study, disaggregated as in IPCC AR5.

	1990-1999	2000-2009	2010-2014
	$GtCO_2/y$		
Net forest-related anthropogenic emissions (1)	**-0.68**	**-0.54**	**-0.55**
Residual forest sink (2)	-1.87	-2.24	-2.35

(1) Estimated based on ref.[28] (which updates the values in IPCC AR5, based on ref.[27]), including deforestation and the impact of direct anthropogenic effects (e.g., afforestation, harvest, secondary forest regrowth) on existing forests.

(2) Estimated by DGVMs, including indirect anthropogenic and natural effects on all the forest area. Note that in IPCC AR5 the residual sink is estimated as difference from all the other terms of the carbon budget.

This study proposes a different disaggregation, which allows separating deforestation and then summing all the direct, indirect and natural effects occurring in existing secondary forests (i.e. bookkeeping model[28] plus DGVMs, numbers in bold in Table SI 11), i.e. the area under the blue line in Fig. 3c plus the area under the right part of red line in Fig 3c. This disaggregation allows global model estimates to be conceptually more comparable with the estimates reported by GHGIs, especially when expressed on an area basis (see red numbers in Tables SI 11 and SI 12). Most GHGIs include part or all of recent indirect anthropogenic effects.

Table SI 11. Forest-related CO_2 emissions (+) and removals (-) for developed countries: values from global models as in Table SI 10, but disaggregated as proposed in this study. Fluxes from existing forests are expressed also on a area basis.

		Source	1990-1999				2000-2009				2010-2014			
			$GtCO_2/y$		*000 Mha*	tCO_2/y/ha	$GtCO_2/y$		*000 Mha*	tCO_2/y/ha	$GtCO_2/y$		*000 Mha*	tCO_2/y/ha
Net emissions from deforestation		Houghton	0.14				0.12				0.12			
Net emissions from secondary forests due to direct anthropogenic effects (afforestation, harvest, forest regrowth) and associated area		**Houghton**	-0.82	**-1.82**	*0.66*	**-1.58**	-0.66	**-1.90**	*0.68*	**-1.58**	-0.67	**-1.89**	*0.69*	**-1.52**
Residual forest flux (indirect anthropogenic and natural effects), and associated area	**Secondary forests**	**DGVMs**	-1.00		*1.15*		-1.24		*1.21*		-1.22		*1.24*	
	Primary forests	**DGVMs**	-0.87		*1.07*	-0.81	-1.00		*1.03*	-0.97	-1.13		*0.99*	-1.15

Table SI 12. Forest-related CO_2 emissions (+) and removals (-) for developed countries: data reported by Annex I (developed) countries to UNFCCC. Fluxes from existing forests are expressed also on a area basis.

	1990-1999			2000-2009			2010-2014		
	$GtCO_2/y$	*000 Mha*	tCO_2/y/ha	$GtCO_2$/y	*000 Mha*	tCO_2/y/ha	$GtCO_2/y$	*000 Mha*	tCO_2/y/ha
Net emissions from deforestation	0.20			0.18			0.15		
Net emissions in managed "forest land" and associated area	**-1.99**	*1.52*	**-1.31**	**-2.24**	*1.55*	**-1.44**	**-2.35**	*1.61*	**-1.46**
Area of unmanaged forests	NE	*0.34*		NE	*0.38*		NE	*0.35*	

Our proposed disaggregation of global models has implications for historical land-related estimates. According to IPCC AR5 WG III Summary for Policy Makers (SPM)[54], the AFOLU (Agriculture, Forestry and Other Land Uses) sector is collectively responsible for 24% of total anthropogenic emissions in 2010 (≈12 $GtCO_2eq/y$, approximately equally spitted between "Agriculture" and "Forestry and Other Land Uses"). This estimate, however, was based on only the EDGAR database. The IPCC AR5 WG III AFOLU chapter[53] chapter assessed also different databases[55], i.e. FAOSTAT[56] and the Houghton bookkeeping model[27]. For non-CO_2 fluxes from Agriculture, the EDGAR database is relatively similar to the FAOSTAT database. However, for CO_2 fluxes from Forestry and Other Land Use (FOLU - considered equivalent to LULUCF) EDGAR has different results to both FAOSTAT and to the Houghton bookkeeping model due to a very different approach[55], not considered by that chapter to properly reflect LULUCF. Thus, for the period 2000-2009, table 11.1 in the IPCC AR5 WG III AFOLU chapter[53] estimated emissions at 4.0 $GtCO_2eq/y$ based on the bookkeeping model[27] only. An update of the estimates from the databases above has been provided by ref.[55]..

The disaggregation proposed above, following the countries' approach to estimate the "anthropogenic" forest flux, would reduce the IPCC AR5 WG III net emissions for the FOLU (LULUCF) sector by at least 3 $GtCO_2eq/y$ (see Fig. 5 in the main text).

8. The conceptual implications of our analysis for the 2°C trajectory.

Our proposed different disaggregation of global model results for the historical period (see Section 7) would need to be extended in future projections of net anthropogenic emissions. This may also have impacts on the 2°C trajectory, as conceptually illustrated in Figure SI 9.

Making results of global models more comparable to country GHGIs would mean disaggregating the global models' fluxes due to indirect human impacts, now included in the "residual terrestrial sink" (Tab. SI 10), and allocating these to the "anthropogenic" land net flux of secondary forests (Tab. SI 11, Fig SI 9). This means reallocating some emissions between the "anthropogenic" flux and the "residual terrestrial sink", but it does not change the sum of the two fluxes. The shift would help ensuring comparability and consistency between independent scientific estimates and country GHGIs, therefore facilitating a credible Global Stocktake, but would slightly affect the magnitude of the 2°C trajectory for anthropogenic net emissions at the global level. However, the shift would not change the decarbonization pathways consistent with the PA[57], and should not be interpreted to mean that those countries with large sinks in managed land are entitled to emit more.

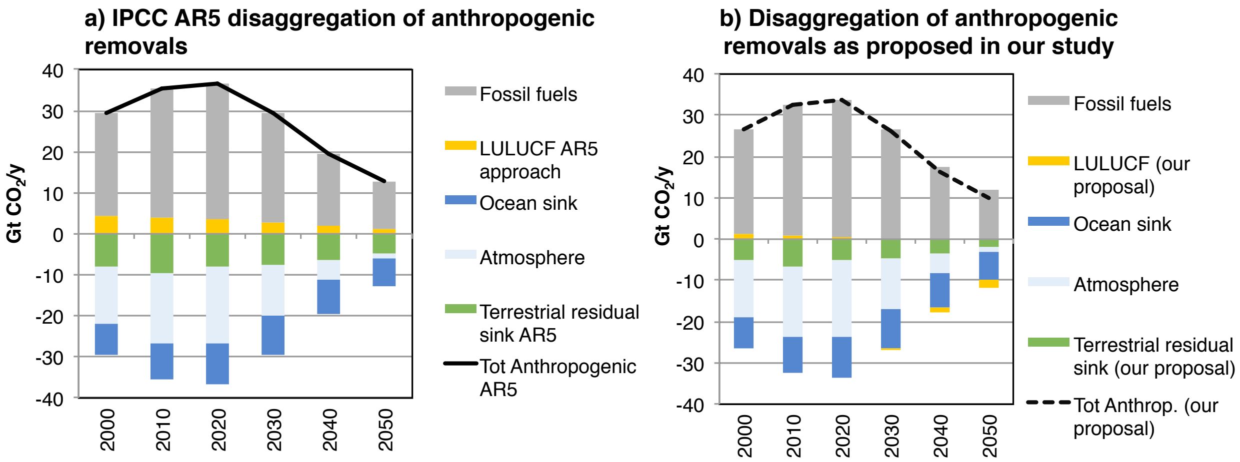

Figure SI 9. The effect of re-allocation of "anthropogenic" land sinks in managed forests on pathways of anthropogenic CO_2 emissions consistent with the IPCC AR5 2°C trajectory up to 2050. Components of the global carbon budget are disaggregated, including fossil fuels and industry and anthropogenic land use (LULUCF) net emissions, balanced by the atmosphere and natural carbon sinks on land and in the ocean (ref.[58], RCP 2.6 values from Tables AII 2.1b, 2.1c, 3.1a, 3.1b). The "anthropogenic" sink is identified following (a) the IPCC AR5 approach, or (b) following the proposal in this study, aimed at ensuring greater consistency with country GHGIs. The sink associated with indirect effects and with a larger area of managed land in GHGIs is allocated to "terrestrial residual sink" (natural) in (a) and to "LULUCF" (anthropogenic) in (b). The amount of sink re-allocated from (a) to (b) has been simplistically assumed to be constant over time and equal to 3 $GtCO_2e$/y (see main paper).

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