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

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Abstract

Achieving the long-term temperature goal of the Paris Agreement (PA) requires forest-based mitigation. Collective progress towards this goal will be assessed by the PA's Global Stocktake. Currently, there is about a 4 $GtCO_2$/y discrepancy in global anthropogenic net land use emissions between global models (reflected in IPCC Assessment Reports) and aggregated national greenhouse gas (GHG) inventories (under the UNFCCC). We show that this discrepancy is largely explained (about 3.2 $GtCO_2$/y) by conceptual differences in anthropogenic forest sink estimation, related to representation of environmental change impacts and the areas considered 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 deepens understanding of model-inventory differences, allowing more transparent analysis of forest-based mitigation and facilitating a more meaningful Global Stocktake.

The Paris Agreement (PA) long-term goals 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 greenhouse (GHG) emissions, while also creating net CO_2 sinks (negative emissions)[3], especially in forests[4–6].

The PA includes an Enhanced Transparency Framework, to track countries' progress towards achieving their individual targets (i.e., the Nationally Determined Contributions, NDCs), and a periodic Global Stocktake, to assess the countries' collective progress towards the long-term goals of the PA in light of the "best available science". The Global Stocktake is potentially the engine of the PA, 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 United Nations Framework Convention on Climate Change (UNFCCC). Given the progress in climate negotiations and the close linkage between the UNFCCC and Intergovernmental Panel on Climate Change (IPCC) processes (see Methods), we assume that inputs to the Global Stocktake will use scientific estimates of GHG trajectories for "well-below 2°C" (summarized by the IPCC 6th Assessment Report, AR6) as the "benchmark" against 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 $GtCO_2/y$ for the 2000s in global anthropogenic land-related GHG emission estimates, with lower values reported in National Greenhouse Gas Inventories (GHGIs) compared to global modelling approaches[8] used in the IPCC 5th Assessment Report (AR5). A suggested reason for this discrepancy is the different approaches to estimate the anthropogenic forest CO_2 removal (i.e. sink)[5]. Updated model[9] and GHGI estimates widen this gap to about 4 $GtCO_2/y$ for the period 2005-2014 (Fig. 2), i.e. 10% of total anthropogenic CO_2 emissions in this period[10]. Understanding and reconciling this discrepancy is essential for the Global Stocktake.

Both the countries' GHGIs, following the IPCC methodological Guidelines[11], and the global models assessed in the IPCC ARs, aim to identify anthropogenic GHG fluxes. This is challenging as land-related fluxes are simultaneously determined by natural and anthropogenic processes, and are 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]), (i) "direct human-induced effects", including land-use changes and management practices, (ii) "indirect human-induced effects", such as human-induced environmental changes (e.g., temperature, precipitation, CO_2 and nitrogen deposition feedbacks) that affect growth, mortality, decomposition rates and natural disturbances regimes, and (iii) "natural effects", including climate variability and a 'background' natural disturbance regime.

Due to differences in purpose and scope, the largely independent scientific communities supporting the IPCC Guidelines (reflected in country GHGIs) and the IPCC ARs 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, 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 GHG inventory 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 (SI section 1). The quality of GHGIs, while varying 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", i.e. "where human interventions and practices have been applied to perform production, ecological or social functions"[11] (SI section 1). The contribution of natural effects on managed lands is assumed negligible over time[12]. GHG fluxes from "unmanaged land" are not reported in GHGIs[14] because they are assumed non-anthropogenic.

The specific land processes included in GHGIs depend on the estimation method used, which differ in approach and complexity among countries (SI section 3). Most countries report both direct and indirect human-induced and natural effects on managed lands (see Tab. 1 and Fig. 3b). The reported estimates may then be filtered through agreed "accounting rules" - i.e., what 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] (SI section 1).

Under the PA, the tracking of individual countries' progress towards NDCs will be based on their accounting approaches. However, the Global Stocktake requires absolute values of global net anthropogenic emissions, i.e., the reporting of country GHG fluxes seen by the atmosphere (or expected to be seen in the future) from managed lands (see Methods).

Global Carbon Cycle Modeling Community

Two fundamentally different types of global models are currently 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 of Houghton[8] has been used as the reference estimate for the anthropogenic land flux in both the IPCC AR5[20,21] and the Global Carbon Project[10]. This model aims to capture only the 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 (e.g., CO_2 fertilization, climate, N deposition). However, the average biomass densities used in the model are based on relatively recent (1970–2010) observations and thus implicitly include impacts of prior 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 (e.g., 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 SI 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 affected by land cover change/management. While DGVMs are conceptually more similar to GHGIs in estimating the anthropogenic fluxes on a given area, their definition of "managed" land is more similar to the bookkeeping approach, i.e., area experiencing management activities represented in the models.

IPCC AR5 versus GHGIs

The conceptual differences between IPCC 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 (i.e., direct, indirect and natural effects), with some differences in practice depending on methods applied (SI section 3). The IPCC AR5, in contrast, disaggregates GHG fluxes into a "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 it is influenced by management practices[23]). Thus, in the IPCC AR5 most of the indirect effects are included in the residual flux, while 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 GHGIs' managed land concept is broader[14] and may include management activities related to the social and ecological functions of land (SI section 1). Therefore, the managed land area considered by GHGIs is typically larger than that of global models.

Toward 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 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 IPCC AR5 anthropogenic flux, i.e., blue box in Fig. 3c) with those associated with indirect and natural effects on managed forest (part of the IPCC AR5 residual sink, i.e. 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 IPCC 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 (S2, i.e., without land-use change, see Methods). We used the Land-Use Harmonization data set (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.

We first focus on developed countries (Fig. 4), which include complete time series of GHGIs for the period 1990-2014. We then provide estimates for the most important (in terms of 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).

For developed countries (Fig. 4), in the period 1990-2014 the bookkeeping estimates of net sink of secondary forests are about 1.5 $GtCO_2$/y 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 (respectively, about 0.13 $GtCO_2$/y and 0.17 $GtCO_2$/y in the period 1990-2014). The secondary forest sink from DGVMs tends to increase over time (SI section 5), consistent with the enhanced net sink modeled in northern extratropical regions[10,22,25] attributed to increasing atmospheric CO_2. This trend is confirmed by faster tree growth measured over the last decades (e.g. 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 area of both the bookkeeping model and the LUH2-v2h data set is 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 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, including: a possible underestimation of the sink by GHGIs because they do not fully include indirect effects, see Tab. 1, or the sink of pools other than biomass (see SI section 6a for a comparison with other global-level assessments[28]); the bookkeeping model including some indirect effects (SI Section 3); or our post-processing of DGVMs resulting in over-estimating the forest sink.

The analysis for developing countries (Fig. 5, central columns) is less complete and more uncertain due to data limitation (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 $GtCO_2$/y) and in GHGIs (about 3.0 $GtCO_2$/y), confirming previous analyses[7,29]. Second, the wide discrepancy (about 1.6 $GtCO_2$/y) 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 bookkeeping model and DGVMs becomes 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 $GtCO_2$/y in the period 2005-2014 using updated estimates, Fig. 2) is associated mostly (80%, or 3.2 $GtCO_2$/y, Fig 5a, right columns) with managed forest sink estimates, and not with deforestation. The remaining 20% is likely due to non-forest land uses (e.g. crops, pastures), considered by the bookkeeping model and only partially by GHGIs, and to other processes (e.g. 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), as also confirmed by a number of detailed country case studies (SI sections 6b and 6c). Other factors, not explored here, may contribute to the discrepancy in forest fluxes, such as different forest definitions, legacy effects, data sources and methods[7,18,19,30,31] (SI section 5). The impact of these factors may be further explored in future updates of our analysis, e.g. by extending the comparison of country data with other datasets (e.g., ref.[29,32,33]) and including other bookkeeping models[19] and updated DGVMs 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 IPCC AR5 and country GHGIs (about 4 $GtCO_2$/y 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 the IPCC work (Special Report on Climate Change and Land and AR6) and the PA’s Global Stocktake.

We show that globally about 80% of the above discrepancy (3.2 $GtCO_2$/y), 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 considering fewer management activities on a smaller managed forest area, and include most of the indirect effects on extant forests in the "residual" land response. A simple post-processing approach, disaggregating global models' results, increases their comparability with GHGIs (Figs. 4 and 5, SI section 7).

While differences in scope, methods and datasets will likely preclude complete reconciliation of global model and GHGI estimates, improvements on both sides can help to better understand and attribute 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 (2019) could help by documenting how different methods and data incorporate direct and indirect human effects in the reported estimates (SI section 3). Since the bookkeeping model[9] uses forest data submitted by countries to FAO, it is very important that countries report consistently to UNFCCC and FAO, which currently is not always the case[31]. The voluntary inclusion of information on non-anthropogenic fluxes from unmanaged lands in national reporting, although not used for accounting purposes, would help to understand better the terrestrial ecosystems' response to climate change, including processes in unmanaged land (e.g., fires, permafrost thawing) that are relevant for assessing progress towards the PA goals.

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 PA. For example, through more disaggregated model results (e.g., sinks from primary and secondary forests in each gridcell) and clear information on areas involved, the analysis proposed here can 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 applies also to the modelling of future net emission pathways from Integrated Assessment Models[36], 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" as in 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 SI 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 changing the decarbonization pathways consistent with the PA[3].

In summary, our study highlights that estimates of the "anthropogenic" forest sink in countries' GHG inventories and global models (reflected in IPCC 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 IPCC 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 ARs and the GHG inventories is needed to increase confidence in land-related GHG estimates for the assessment of the collective progress towards the goals of the Paris Agreement.

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Author Contributions

G.G. designed the analysis with J.H. and W.A.K., and all the three drafted the manuscript. G.G. coordinated all the inputs, executed the calculations and made the figures. A.C., R.A.H., G.P.P. and M.S.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.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.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.

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METHODS

Inputs to the Global Stocktake

According to Article 14 of the PA[1], the collective progress towards holding the increase in the global average temperature to well below 2°C above pre-industrial levels (Article 2 of the PA) will be assessed periodically (every 5 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 PA). 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" greenhouse (GHG) gas emissions[52].

To support the PA, 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 (GHGIs), three Special Reports (on 1.5°C, land and oceans, to be completed in 2018 and 2019), and the 6th Assessment Report (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: (i) globally aggregated country data on anthropogenic net emissions: either from existing GHG reporting obligations or expected under the Enhanced Transparency Framework (see SI 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; and (ii) independent scientific estimates (including estimates summarized in the IPCC 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 "benchmark" against which the aggregated country data will be assessed to identify the "emissions gap"[51,54,55]. Consistent with this assumption, in 2022 (i.e., in time to be used by the Global Stocktake) the contribution of Working Group III to IPCC 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 because such lands can contribute important 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 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", aimed to reflect only the impact of individual country's mitigation actions[15].

For assessing the collective progress toward the "balance" between GHG emissions and removals, the Global Stocktake will require globally aggregated values of absolute net anthropogenic land GHG emissions, i.e. 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 PA. For the forward-looking assessment, these absolute values need to be extracted from the NDCs or country's projections, which may have applied specific accounting rules (SI section 1) that may affect the estimated fluxes[5]. For example, a country may use a "forest reference level" (i.e., 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 toward its 2030 NDC target. In the case where areas of managed forest are already a sink and expected to still be 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, while 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 UNFCCC

A general description of country GHGI estimation, reporting, accounting and review under the UNFCCC is included in SI section 1.

Global LULUCF country CO_2 data in Fig. 2 (1990-2014) are updated to February 2016 (from[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 developing country data in Fig. 2 include some non-CO_2 emissions. However, this contribution is assumed to be very small, e.g., 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 forest CO_2 fluxes of developed countries (Fig. 4), most of which have a consolidated experience in GHGIs and more detailed and robust information that many developing countries' GHGIs. 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. While the lack of specific forest CO_2 flux data in many developing countries prevents us to provide a complete global analysis, our study is globally relevant, because global data in Fig. 5 cover about 80% of the FAO-FRA's global "secondary forest" area (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 (UNFCCC Annex I): The following 40 countries are included in this study (Table SI 4): Australia, Belarus, Canada, EU (28 countries), Japan, Kazakhstan, New Zealand, Norway, Russian Federation, Switzerland, Turkey, Ukraine and USA. 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 GHG, here 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 SI section 1), even if this concept is explicit only in few GHGIs[14] (e.g. US, 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 Table SI 2).

Developing countries (UNFCCC non-Annex I): 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], occasionally gap-filled with FAO-FRA 2015 for forest area only (using data for "secondary" and "planted" forests), see Table SI 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 (i.e., forest degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks, which we considered all being part of the "forest land" category).

After the filters above, we were able to collect forest CO_2 flux estimates from about 50 developing countries, including (Table SI 5) 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, Republic of Korea, South Africa, Swaziland, Tunisia, Uganda, Uruguay, Venezuela, Vietnam (plus other smaller countries).

The use of either 2003 or 2006 IPCC methodological guidance implies use of the "managed land proxy", even if rarely mentioned (e.g., Brazil[14]). Several developing countries do not report unmanaged lands[31], implicitly considering all forests managed. Due to frequent lack of precise methodological information, for many developing countries it is difficult to draw precise conclusions on the role of indirect anthropogenic effects on GHGI estimates. Nevertheless, based on the available information (see SI section 3, Tab. SI 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, i.e. 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.

While many developing countries report some data on LULUCF net emissions[5], not many report explicitly emissions from deforestation. An approximate estimate of emissions from deforestation in developing countries for the period 2005-2014 was derived starting from their total LULUCF emissions (around 2 $GtCO_2$/y, based on an update of ref.[5]) and then subtracting their net forest CO_2 flux from GHGIs estimated above (around -1.6 $GtCO_2$/y including "forest land" category but excluding deforestation, see Fig 5a, central green column) and the emissions from peat fires and decomposition (around 0.6 $GtCO_2$/y, reported by Indonesia). This approach simplistically assumes that net emissions from non-forest land uses are negligible.

The values of GHGIs' uncertainty (+/- 1 SD) in Figs. 4 and 5 are based on the information reported in countries' GHG reports, following the methodology described in the SI of ref.[5]. According to this information, the uncertainty of forest-related fluxes (expressed as 95% CI, 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 where no information on uncertainty was available. This information was then converted into +/- 1 SD for this paper.

Bookkeeping Model

Houghton's 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 USA and SE 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 over 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, e.g., 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 (FC); forest conversion to pasture or abandonment of pasture back to forest (FP); 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 (FCO); forest or other land converted to planted forest (PLANT); industrial wood harvest (IND); fuelwood harvest (FUEL); and fire emissions (FIRE, only for USA among developed countries).

The values of uncertainty (+/- 1 SD) 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].

Dynamic Global Vegetation Models (DGVMs)

The IPCC Fifth Assessment Report (AR5)[21] and the Global Carbon Project (GCP)[10] assess land model intercomparisons that have been coordinated by the project "Trends and drivers of the regional-scale sources and sinks of carbon dioxide (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 (e.g., wood harvest) in the simulations (e.g., 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, based on HYDE, but providing 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, and including 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 data set was extrapolated by country for pastures and cropland separately based on the trend in agricultural area over the previous 5 years. The HYDE data set is independent from the data set used in the bookkeeping model[9], which is based primarily on forest area change statistics. Furthermore, although 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 (e.g., 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 of 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 in broad plant functional types (PFT) and use average characteristics of each PFT within rather coarse resolution gridcells (0.5° or coarser). Not all TRENDY models simulate wood harvest or fire, and most do not simulate forest age-class distributions (see Tab. SI 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 (i.e., 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 (i.e., 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" etc.). Overall, this suggests that at 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) to be conceptually comparable, respectively, to unmanaged and managed forest. "Secondary" in the LUH2-v2h datasets refers to land previously disturbed by human activities (post-850 AD) and recovering. We therefore extracted the fraction of primary and secondary forest area per grid cell from the LUH2-v2hn 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 have no forests during the period 1990-2014 in 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 gridcell), 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 summarised in Tab SI 7.

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

The values of uncertainty (+/- 1 SD) 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 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.

Additional REFERENCES for the Methods section

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Table 1. Processes included in each of the datasets used in our analysis: Bookkeeping model[9], DGVMs and countries' GHGIs 2018. DGVMs include results from the TRENDY model intercomparison runs version 4 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.

	Direct anthropogenic effects			**Recent indirect anthro-pogenic effects on managed/ secondary forests**	**Natural effects on managed/ secondary forests**	**Indirect 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 (1)	x	x	x			
DGVMs (CO_2 and climate change only runs) (2)				x	x	x
Used in the sum of Bookkeeping model and DGVMs (3)	Houghton			DGVMs		
Country GHGIs	x	x	x	mostly yes (4)	x	

(1) This includes all forest-related C fluxes (excluding deforestation), see Methods. Blue columns in Figures 4 and 5.

(2) See Table SI 6 for additional details on DGVMs. Orange columns in Figures 4 and 5.

(3) Grey columns in Figures 4 and 5.

(4) Green columns in Figures 4 and 5. 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 countries' GHGIs corresponding to 87% of the total forest net GHG flux and to 73% of total managed forest area reported in the GHGIs (see Table SI 2). Exceptions, i.e., where recent indirect effects are mostly not captured, are Australia, Canada, Japan and few EU countries (e.g. Czech Rep., Italy, Romania, 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 (i.e. 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 Table SI 2).

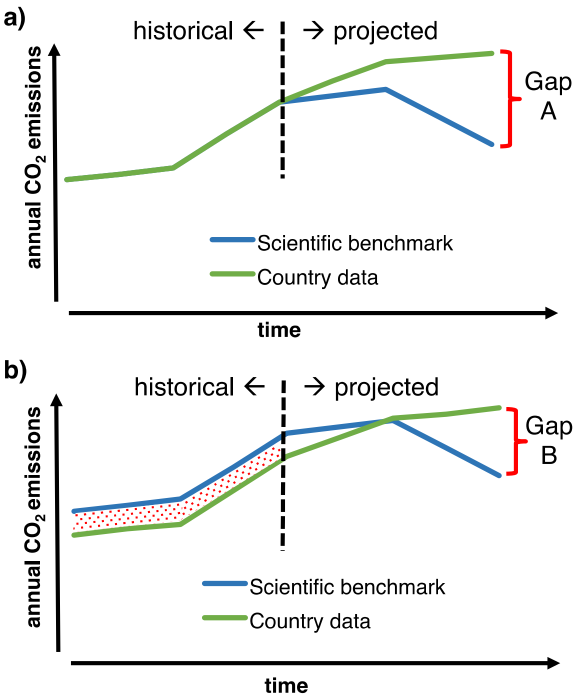


Figure 1. Conceptual diagram of the impact of mismatches in anthropogenic land flux estimates on the gap between country pledges and what is required to meet climate targets. The Global Stocktake's assessment of the collective progress toward the long-term targets of the Paris Agreement will likely benchmark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

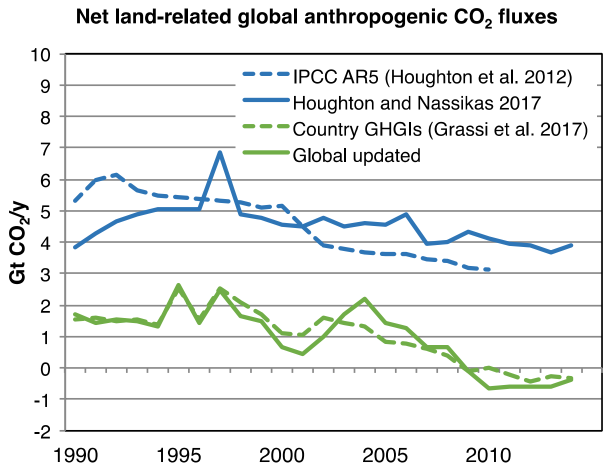


Figure 2. Comparison of the global net anthropogenic land-related CO_2 fluxes estimated by the IPCC 5th Assessment Report (AR5) and countries' Greenhouse Gas Inventories (GHGIs). The flux in IPCC AR5 WGI table 6.1[20] and WGIII table 11.1[21] was based on the Houghton bookkeeping model ref.[8] (dashed blue line), updated in this figure using ref.[9] (solid blue line). This is compared with countries' GHGIs ref.[5] (dashed green line), updated in this study (solid green line). The gap between the updated estimates is about 4 $GtCO_2$/y for the period 2005-2014. Positive signs indicate net emissions, negative signs indicate net removals of CO_2 from the atmosphere. See Methods for details.

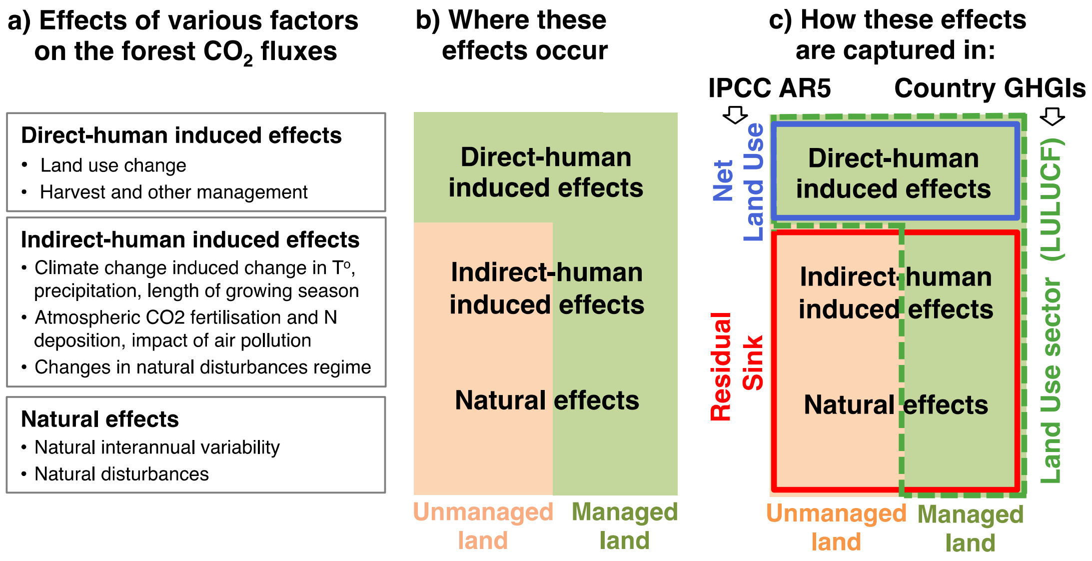


Figure 3. Summary of the main conceptual differences in defining the "anthropogenic land CO_2 flux" between IPCC[20,21] and countries' GHG inventories (GHGIs). (a) Effects of key processes on the land flux as defined by IPCC[12]; (b) Where these effects occur (in unmanaged/primary lands, vs. managed/secondary lands); (c) How these effects are captured: In the IPCC 5th Assessment Report (AR5) the anthropogenic "net land use" from ref.[8] (solid blue line, including only direct human-induced effects), and the non-anthropogenic "residual sink" (solid red line, calculated by difference from the other terms in the global carbon budget[20,21]); countries' anthropogenic land flux from GHGIs reported to UNFCCC (under the "Land Use, Land-Use Change and Forestry" sector, LULUCF, green dashed line), which in most cases includes direct and indirect human-induced and natural effects in an area of "managed" land that is broader than the one considered by ref.[8], (see Table 1 and SI section 3).

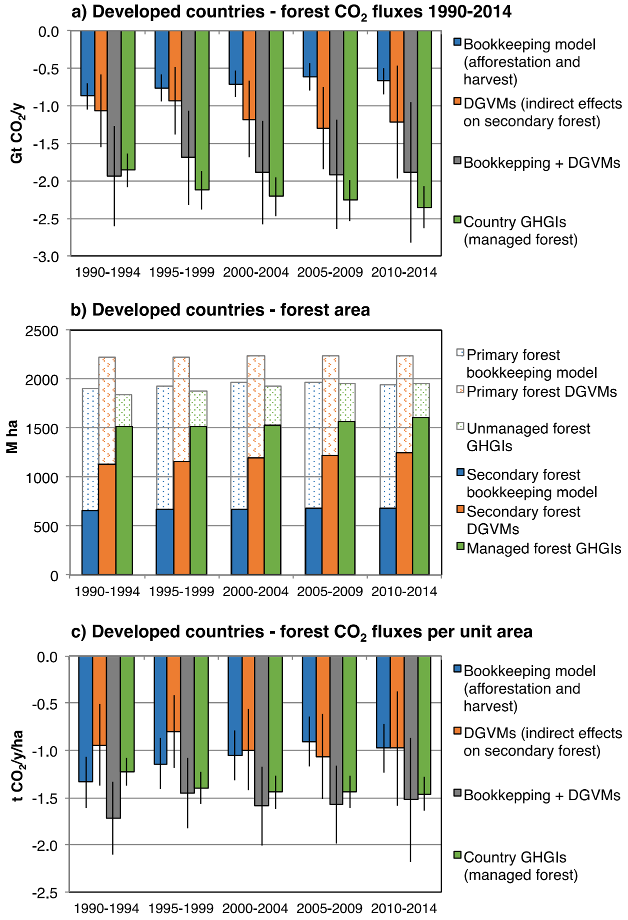
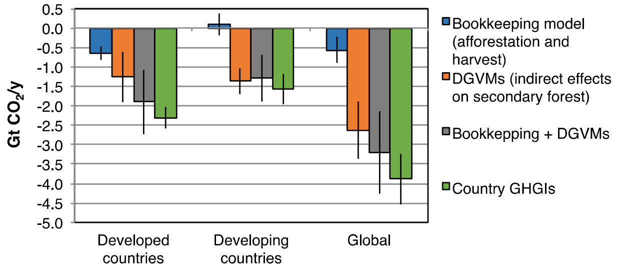
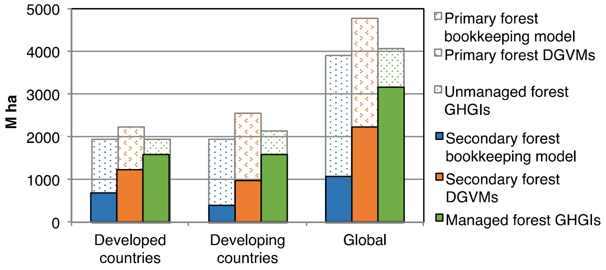


Figure 4. Comparison and reconciliation of developed countries' forest net CO_2 fluxes and forest area in the period 1990-2014 between global models and countries' GHG inventories (GHGIs). (a) Net CO_2 flux from secondary/managed forests (including afforestation, but excluding deforestation); (b) Forest 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" (considered here conceptually comparable to "managed forest") refers to area classified as forest in the period analyzed 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 panel (c) (bookkeeping + DGVMs) is estimated as the grey column in panel (a) divided by the orange column only in panel (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 DGVMs secondary forest area. Whiskers express +/- 1 SD.

a) Global and regional forest CO_2 fluxes - 2005-2014



b) Global and regional forest area



c) Global and regional forest CO_2 fluxes per unit area

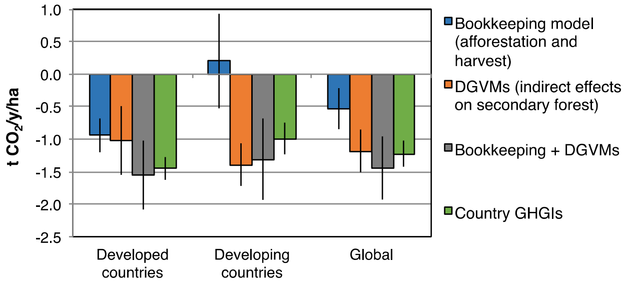


Figure 5. Comparison and reconciliation of global forest net CO_2 fluxes and forest area in the period 2005-2014 between global models and countries' GHG inventories. (a) Net CO_2 flux from secondary/managed forests (including afforestation, excluding deforestation, peat fire and peat decomposition); (b) Forest area; (c) Net CO_2 fluxes from secondary/managed forests per unit area. From bookkeeping model[9], DGVMs, and country GHGIs (see Methods). "Managed forest", "Secondary forest" and the grey column in panel (c) are estimated as in Fig. 4. While our analysis does not include all developing countries, it covers about 80% of the FAO-FRA's global "secondary forest" area. Whiskers express +/- 1 SD.