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1 Reconciling global model estimates and country reporting of 2 anthropogenic forest CO₂ sinks

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42

43 **Abstract**

44 Achieving the long-term temperature goal of the Paris Agreement (PA) requires forest-based
45 mitigation. Collective progress towards this goal will be assessed by the PA's Global
46 Stocktake. Currently, there is about a 4 GtCO₂/y discrepancy in global anthropogenic net
47 land use emissions between global models (reflected in IPCC Assessment Reports) and
48 aggregated national greenhouse gas (GHG) inventories (under the UNFCCC). We show that
49 this discrepancy is largely explained (about 3.2 GtCO₂/y) by conceptual differences in
50 anthropogenic forest sink estimation, related to representation of environmental change
51 impacts and the areas considered managed. For a more credible tracking of collective
52 progress under the Global Stocktake, these conceptual differences between models and
53 inventories need to be reconciled. We implement a new method of disaggregation of global
54 land model results that allows greater comparability with GHG inventories. This deepens
55 understanding of model-inventory differences, allowing more transparent analysis of forest-
56 based mitigation and facilitating a more meaningful Global Stocktake.

57

58

59 The Paris Agreement (PA) long-term goals include holding “the increase in the global
60 average temperature to well below 2°C” (Article 2) and require achieving globally “...a
61 balance between anthropogenic emissions by sources and removals by sinks of greenhouse
62 gases in the second half of this century ...” (Article 4)¹. It is generally understood that
63 “anthropogenic” applies to both “emissions” and “removals”². Reaching this balance
64 requires a simultaneous dramatic reduction of fossil fuel and land-based greenhouse (GHG)
65 emissions, while also creating net CO₂ sinks (negative emissions)³, especially in forests⁴⁻⁶.

66 The PA includes an Enhanced Transparency Framework, to track countries’ progress
67 towards achieving their individual targets (i.e., the Nationally Determined Contributions,
68 NDCs), and a periodic Global Stocktake, to assess the countries’ collective progress towards
69 the long-term goals of the PA in light of the “best available science”. The Global Stocktake
70 is potentially the engine of the PA, because any identified “emission gap” between
71 “collective progress” and the “well-below 2°C trajectory” is expected to motivate increased
72 mitigation ambition by countries in successive rounds of NDCs.

73 The details of the Global Stocktake are still to be defined under the United Nations
74 Framework Convention on Climate Change (UNFCCC). Given the progress in climate
75 negotiations and the close linkage between the UNFCCC and Intergovernmental Panel on
76 Climate Change (IPCC) processes (see Methods), we assume that inputs to the Global
77 Stocktake will use scientific estimates of GHG trajectories for “well-below 2°C”
78 (summarized by the IPCC 6th Assessment Report, AR6) as the “benchmark” against which
79 the planned collective progress (based on country reports) will be compared to assess the
80 emission gap (Fig. 1a). This approach requires that scientific estimates and country data are
81 comparable and consistent for the historical period (Fig. 1b).

82 Recent studies^{5,7} highlighted a discrepancy of about 3 GtCO₂/y for the 2000s in global
83 anthropogenic land-related GHG emission estimates, with lower values reported in National
84 Greenhouse Gas Inventories (GHGIs) compared to global modelling approaches⁸ used in the
85 IPCC 5th Assessment Report (AR5). A suggested reason for this discrepancy is the different
86 approaches to estimate the anthropogenic forest CO₂ removal (i.e. sink)⁵. Updated model⁹
87 and GHGI estimates widen this gap to about 4 GtCO₂/y for the period 2005-2014 (Fig. 2),
88 i.e. 10% of total anthropogenic CO₂ emissions in this period¹⁰. Understanding and
89 reconciling this discrepancy is essential for the Global Stocktake.

90 Both the countries’ GHGIs, following the IPCC methodological Guidelines¹¹, and the global
91 models assessed in the IPCC ARs, aim to identify anthropogenic GHG fluxes. This is
92 challenging as land-related fluxes are simultaneously determined by natural and
93 anthropogenic processes, and are the most uncertain component of the global carbon
94 budget¹⁰. Three types of “effects” can drive land GHG fluxes (see Fig. 3a, building on ref.¹²),
95 (i) “direct human-induced effects”, including land-use changes and management practices,
96 (ii) “indirect human-induced effects”, such as human-induced environmental changes (e.g.,
97 temperature, precipitation, CO₂ and nitrogen deposition feedbacks) that affect growth,
98 mortality, decomposition rates and natural disturbances regimes, and (iii) “natural effects”,
99 including climate variability and a ‘background’ natural disturbance regime.

100 Due to differences in purpose and scope, the largely independent scientific communities
101 supporting the IPCC Guidelines (reflected in country GHGIs) and the IPCC ARs have

102 developed different approaches to identify anthropogenic GHG fluxes. Both approaches are
103 valid in their own specific contexts, yet both are also incomplete.

104 Here we show the main conceptual differences between country GHGIs and global models
105 when estimating the “anthropogenic” net sink, and propose and evaluate a disaggregation of
106 forest net CO₂ flux estimates by global models to facilitate a comparison with GHGIs. Our
107 main focus is on developed countries, where the analysis is based on detailed and
108 consolidated country data. We also provide estimates for developing countries, less robust
109 due to data limitations, to highlight the global relevance of our analysis. Finally, we discuss
110 the implications of our findings in the context of the ongoing IPCC work programme, the
111 country GHG reporting to the UNFCCC, and the Global Stocktake.

112

113 **UNFCCC GHG inventory community**

114 All Parties to the UNFCCC are required to report national GHGIs of anthropogenic
115 emissions and removals, with different obligations for developed and developing countries
116 (SI section 1). The quality of GHGIs, while varying between countries, is gradually
117 improving over time^{7,13}.

118 Due to the difficulty in providing widely applicable and scientifically robust methods to
119 disentangle direct and indirect human-induced and natural effects on land-based GHG
120 fluxes, the IPCC Guidelines adopted the “managed land” concept¹¹ as a pragmatic proxy to
121 facilitate GHGI reporting. “Anthropogenic” land GHG fluxes (direct and indirect) are
122 defined as all those occurring on “managed land”, i.e. “where human interventions and
123 practices have been applied to perform production, ecological or social functions”¹¹ (SI
124 section 1). The contribution of natural effects on managed lands is assumed negligible over
125 time¹². GHG fluxes from “unmanaged land” are not reported in GHGIs¹⁴ because they are
126 assumed non-anthropogenic.

127 The specific land processes included in GHGIs depend on the estimation method used,
128 which differ in approach and complexity among countries (SI section 3). Most countries
129 report both direct and indirect human-induced and natural effects on managed lands (see
130 Tab. 1 and Fig. 3b). The reported estimates may then be filtered through agreed “accounting
131 rules” - i.e., what countries actually count towards their mitigation targets¹⁵. These may aim
132 to better quantify the additional mitigation actions by, for example, factoring out the impact
133 of natural disturbances¹⁶ and of forest age-related dynamics^{15,17} (SI section 1).

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

138

139 **Global Carbon Cycle Modeling Community**

140 Two fundamentally different types of global models are currently used to simulate the CO₂
141 exchange between the terrestrial biosphere and the atmosphere¹⁸: bookkeeping models and
142 Dynamic Global Vegetation Models (DGVMs).

143 Bookkeeping models track changes in the carbon stocks of areas undergoing land use/cover
144 change using predefined rates of growth and decay for vegetation and soil carbon^{8,19}. The
145 bookkeeping model of Houghton⁸ has been used as the reference estimate for the
146 anthropogenic land flux in both the IPCC AR5^{20,21} and the Global Carbon Project¹⁰. This
147 model aims to capture only the direct anthropogenic effects, including deforestation,
148 afforestation/reforestation and wood harvest (see Methods). By keeping rates of growth and
149 decay constant over the course of a simulation, the model attempts to exclude the indirect
150 and natural effects from environmental changes (e.g., CO₂ fertilization, climate, N
151 deposition). However, the average biomass densities used in the model are based on
152 relatively recent (1970–2010) observations and thus implicitly include impacts of prior
153 environmental changes. The global carbon budget^{10,20,21} balances the bookkeeping flux from
154 land and fossil fuel emissions, with the measured atmospheric increase and the natural
155 response of ocean and land sinks to anthropogenic and environmental change (e.g., indirect
156 effects). Until recently¹⁰, this natural land sink was calculated as the residual of all other
157 terms in the carbon budget (the “residual terrestrial sink”).

158 DGVMs simulate ecosystem processes (primary productivity, autotrophic and heterotrophic
159 respiration), their response to changing CO₂, climate, land cover transitions and, depending
160 on the model, additional processes such as management and natural disturbances^{10,22} (see
161 Methods and SI section 4). Within this class of models the anthropogenic and non-
162 anthropogenic fluxes are quantified by taking the difference between model runs with and
163 without land-cover change (and management, if modelled)¹⁰. Thus, the anthropogenic net
164 land CO₂ flux includes the models’ estimates of direct, indirect and in some cases natural fire
165 effects on land affected by land cover change/management. While DGVMs are conceptually
166 more similar to GHGIs in estimating the anthropogenic fluxes on a given area, their
167 definition of “managed” land is more similar to the bookkeeping approach, i.e., area
168 experiencing management activities represented in the models.

169

170 **IPCC AR5 versus GHGIs**

171 The conceptual differences between IPCC AR5 and GHGIs in estimating the anthropogenic
172 land flux are shown in Fig 3c. Most GHGIs include the majority of fluxes occurring on
173 managed lands (i.e., direct, indirect and natural effects), with some differences in practice
174 depending on methods applied (SI section 3). The IPCC AR5, in contrast, disaggregates
175 GHG fluxes into a “net land use” (mostly associated with direct effects in the bookkeeping
176 model) and a “residual sink” (associated with responses of all land to indirect and natural
177 effects, although some studies suggested it is influenced by management practices²³). Thus,
178 in the IPCC AR5 most of the indirect effects are included in the residual flux, while in most
179 GHGIs they are largely included in estimated fluxes from managed lands.

180 Global models and the GHGIs consider fluxes from deforestation and
181 afforestation/reforestation as direct anthropogenic fluxes but differ in the treatment of
182 managed forests. The bookkeeping model⁹, some DGVMs and GHGIs estimate land
183 management (wood harvest and regrowth), but the GHGIs’ managed land concept is
184 broader¹⁴ and may include management activities related to the social and ecological

185 functions of land (SI section 1). Therefore, the managed land area considered by GHGIs is
186 typically larger than that of global models.

187

188 **Toward reconciling estimates**

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

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

197 Our estimates associated with direct effects are from a recent bookkeeping analysis⁹, which
198 is an updated version of IPCC AR5⁸ (see Methods). We then derived fluxes associated with
199 recent indirect and natural effects on managed forests from the post-processing of results
200 from nine DGVMs from the TRENDY-v4 project^{22,24}, using model runs with CO₂ and
201 climate change only (S2, i.e., without land-use change, see Methods). We used the Land-Use
202 Harmonization data set (LUH2-v2h, see Methods) to divide the forest flux between
203 “primary” and “secondary” forests, assuming that secondary forests are comparable to
204 managed forests under GHGIs and that the response of primary and secondary forests to
205 environmental change is the same.

206 We first focus on developed countries (Fig. 4), which include complete time series of GHGIs
207 for the period 1990-2014. We then provide estimates for the most important (in terms of
208 forest sink) developing countries and at the global level (Fig. 5), limited by data availability
209 to the period 2005-2014. Given our focus on the forest CO₂ sink, the results presented
210 include all existing forests (including forest management, forest regrowth, afforestation and
211 forest degradation), but exclude deforestation and peat-related emissions (see Methods).

212 For developed countries (Fig. 4), in the period 1990-2014 the bookkeeping estimates of net
213 sink of secondary forests are about 1.5 GtCO₂/y lower than those reported in GHGIs, and
214 show an opposite trend (Fig. 4a). The sink in the bookkeeping model slightly decreases over
215 time, due to increasing wood harvest levels and forest aging in most countries. Deforestation
216 fluxes (not shown in Fig. 4) are small and of similar magnitude in the bookkeeping model
217 and country GHGIs (respectively, about 0.13 GtCO₂/y and 0.17 GtCO₂/y in the period 1990-
218 2014). The secondary forest sink from DGVMs tends to increase over time (SI section 5),
219 consistent with the enhanced net sink modeled in northern extratropical regions^{10,22,25}
220 attributed to increasing atmospheric CO₂. This trend is confirmed by faster tree growth
221 measured over the last decades (e.g. in Central Europe²⁶), although negative impacts of
222 environmental changes on tree growth and mortality are also observed locally²⁷. When the
223 secondary forest fluxes from DGVMs are added to fluxes from the bookkeeping model, the
224 combined estimates (grey column in Fig. 4a) are much closer to the GHGIs. The secondary
225 forest area of both the bookkeeping model and the LUH2-v2h data set is smaller than the
226 managed forest area in GHGIs (Fig. 4b), although the total forest areas (including
227 primary/unmanaged area) are broadly comparable. When the sum of forest CO₂ fluxes from

228 bookkeeping model and DGVMs is expressed on an area basis (based only on the larger
229 secondary forest area from LUH2-v2h, see Methods), it becomes on average 13% greater
230 than GHGI estimates (Fig. 4c). This discrepancy may be due to various factors, including: a
231 possible underestimation of the sink by GHGIs because they do not fully include indirect
232 effects, see Tab. 1, or the sink of pools other than biomass (see SI section 6a for a
233 comparison with other global-level assessments²⁸); the bookkeeping model including some
234 indirect effects (SI Section 3); or our post-processing of DGVMs resulting in over-
235 estimating the forest sink.

236 The analysis for developing countries (Fig. 5, central columns) is less complete and more
237 uncertain due to data limitation (see Methods). Nevertheless, the pattern that emerges is very
238 similar to that in developed countries. First, deforestation fluxes (not shown on Fig. 5) are
239 large, but in the period 2005-2014 have the same magnitude in the bookkeeping model (3.4
240 GtCO₂/y) and in GHGIs (about 3.0 GtCO₂/y), confirming previous analyses^{7,29}. Second, the
241 wide discrepancy (about 1.6 GtCO₂/y) between the bookkeeping model and GHGIs is
242 largely reconciled by considering indirect effects on secondary forests in DGVMs (Fig. 5a).
243 The small net source estimated by the bookkeeping model is mainly due to increasing rates
244 of wood harvest (often associated with forest degradation), offsetting the sink in forest
245 expansion and regrowth. When differences in areas are taken into account (Fig. 5b), the sum
246 of bookkeeping model and DGVMs becomes 30% greater than GHGI estimates (Fig. 5c).

247 The global-level analysis indicates that the discrepancy in land-related fluxes between the
248 bookkeeping model and GHGIs (about 4 GtCO₂/y in the period 2005-2014 using updated
249 estimates, Fig. 2) is associated mostly (80%, or 3.2 GtCO₂/y, Fig 5a, right columns) with
250 managed forest sink estimates, and not with deforestation. The remaining 20% is likely due
251 to non-forest land uses (e.g. crops, pastures), considered by the bookkeeping model and only
252 partially by GHGIs, and to other processes (e.g. peat fires, peat decomposition). The gap in
253 forest fluxes can be largely reconciled when differences in the consideration of indirect
254 effects and managed forest areas are taken into account (Fig. 5), as also confirmed by a
255 number of detailed country case studies (SI sections 6b and 6c). Other factors, not explored
256 here, may contribute to the discrepancy in forest fluxes, such as different forest definitions,
257 legacy effects, data sources and methods^{7,18,19,30,31} (SI section 5). The impact of these factors
258 may be further explored in future updates of our analysis, e.g. by extending the comparison
259 of country data with other datasets (e.g., ref.^{29,32,33}) and including other bookkeeping
260 models¹⁹ and updated DGVMs results. However, it is unlikely that these factors and
261 additional analyses would contradict our main conclusions.

262

263 **Policy implications and roadmap**

264 This study highlights the main reasons for the large discrepancy in the global net
265 “anthropogenic” land CO₂ flux estimates between the bookkeeping model⁹ used by IPCC
266 AR5 and country GHGIs (about 4 GtCO₂/y for the period 2005-2014 using updated
267 estimates, Fig. 2), and outlines a feasible method to resolve this discrepancy. The outcomes
268 of our study are relevant for both the IPCC work (Special Report on Climate Change and
269 Land and AR6) and the PA’s Global Stocktake.

270 We show that globally about 80% of the above discrepancy (3.2 GtCO₂/y), is related to

271 conceptual differences in anthropogenic forest sink estimates, in both developed and
272 developing countries. Country GHGIs often include estimates from large areas of “managed”
273 forests and the impact of indirect effects (environmental change). Global models, in contrast,
274 estimate the anthropogenic land flux considering fewer management activities on a smaller
275 managed forest area, and include most of the indirect effects on extant forests in the
276 “residual” land response. A simple post-processing approach, disaggregating global models’
277 results, increases their comparability with GHGIs (Figs. 4 and 5, SI section 7).

278 While differences in scope, methods and datasets will likely preclude complete
279 reconciliation of global model and GHGI estimates, improvements on both sides can help to
280 better understand and attribute differences. This leads to the specific recommendations
281 below, for both GHGIs and global models.

282 Country GHGIs should provide more transparent and complete information on managed
283 forests, including maps, harvested area, harvest cycle, forest age and if/how indirect and
284 natural effects are included. The refinement of the IPCC Guidelines (2019) could help by
285 documenting how different methods and data incorporate direct and indirect human effects
286 in the reported estimates (SI section 3). Since the bookkeeping model⁹ uses forest data
287 submitted by countries to FAO, it is very important that countries report consistently to
288 UNFCCC and FAO, which currently is not always the case³¹. The voluntary inclusion of
289 information on non-anthropogenic fluxes from unmanaged lands in national reporting,
290 although not used for accounting purposes, would help to understand better the terrestrial
291 ecosystems’ response to climate change, including processes in unmanaged land (e.g., fires,
292 permafrost thawing) that are relevant for assessing progress towards the PA goals.

293 In parallel, the global modelling community should design future models and model
294 experiments to increase their comparability with historical GHGIs and thus their relevance in
295 the context of the PA. For example, through more disaggregated model results (e.g., sinks
296 from primary and secondary forests in each gridcell) and clear information on areas
297 involved, the analysis proposed here can be used to identify the anthropogenic components
298 of the land flux. Efforts to improve estimates should include a better representation of
299 management^{34,35} and natural disturbances in global models.

300 The above applies also to the modelling of future net emission pathways from Integrated
301 Assessment Models³⁶, used to assess the collective gap between current country mitigation
302 ambition and a “well below 2°C” pathway. These models take the same approach to
303 “anthropogenic” as in the bookkeeping model⁹, and thus tend to estimate lower
304 anthropogenic forest sinks and higher net anthropogenic land emissions than country GHGIs
305 (Fig. 1b). Even if these discrepancies can be harmonized³⁷ or corrected for, they may
306 increase the uncertainty of the emission gap³⁸. Following the more systematic approach
307 developed here, reallocating the environmentally-driven fluxes from managed land
308 (currently a part of the “residual terrestrial sink”) to the “anthropogenic” net land flux (see SI
309 section 8) would increase their comparability and consistency with country mitigation
310 targets. This reallocation would minimize the need for ad-hoc land-related corrections,
311 therefore reducing the uncertainty of the emission gap, without changing the decarbonization
312 pathways consistent with the PA³.

313 In summary, our study highlights that estimates of the “anthropogenic” forest sink in
314 countries’ GHG inventories and global models (reflected in IPCC AR5) are not conceptually

315 comparable. The magnitude of the differences may jeopardize the intent of the Global
316 Stocktake to assess collective progress towards the targets of the Paris Agreement. To
317 minimize this risk, the forthcoming IPCC AR6 will need to assess available literature that
318 provides results with a greater level of disaggregation³⁹. In addition, countries will need to
319 increase the transparency of their GHGIs, including how estimates incorporate indirect
320 human and natural effects in managed lands. Ultimately, greater collaboration between the
321 scientific communities that support the IPCC ARs and the GHG inventories is needed to
322 increase confidence in land-related GHG estimates for the assessment of the collective
323 progress towards the goals of the Paris Agreement.

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328 **Disclaimer:** The views expressed are purely those of the writers and may not in any circumstances be
329 regarded as stating an official position of the European Commission or any other Government
330 Agency

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333 **Author Contributions**

334 G.G. designed the analysis with J.H. and W.A.K., and all the three drafted the manuscript. G.G.
335 coordinated all the inputs, executed the calculations and made the figures. A.C., R.A.H., G.P.P. and
336 M.S.S. contributed to the analysis and provided inputs to the manuscript. F.D. contributed by
337 commenting and editing the manuscript. R.A.V., S.R., S.F. and D.L. contributed to collecting data
338 and information on country GHGIs. R.A. post-processed the DGVM results. R.A.H. and A.N.
339 provided data from bookkeeping models. L.P. provided comments on the Global Stocktake. A.A.,
340 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
341 DGVM results and inputs to the manuscript. All authors read and approved the final manuscript.

342

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478 METHODS

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481 **Inputs to the Global Stocktake**

482 According to Article 14 of the PA¹, the collective progress towards holding the increase in
483 the global average temperature to well below 2°C above pre-industrial levels (Article 2 of
484 the PA) will be assessed periodically (every 5 years starting in 2023) by the “Global
485 Stocktake”. This temperature goal requires reaching a “balance between global
486 anthropogenic greenhouse gas emissions by sources and removals by sinks in the second half
487 of this century” (Article 4 of the PA). A close comparison of Article 4 with other UNFCCC
488 documents points to the exclusion of natural sinks², suggesting that this balance is referring
489 to achieving net zero “anthropogenic” greenhouse (GHG) gas emissions⁵².

490 To support the PA, and particularly the Global Stocktake, the IPCC will release an ambitious
491 set of documents, including the 2019 Refinement to the 2006 IPCC Guidelines for National
492 Greenhouse Gas Inventories (GHGIs), three Special Reports (on 1.5°C, land and oceans, to
493 be completed in 2018 and 2019), and the 6th Assessment Report (AR6, in 2022).

494 In light of the available information (paragraphs 99-101 of UNFCCC Decision 1/CP.21¹ and
495 related countries’ submissions⁵³), this study assumes that the mitigation part of the Global
496 Stocktake will be based on two main sources of input: (i) globally aggregated country data
497 on anthropogenic net emissions: either from existing GHG reporting obligations or expected
498 under the Enhanced Transparency Framework (see SI section 1), including GHGIs in the
499 National Inventory Reports (NIRs) and Biennial Update Reports (BURs) for assessing the
500 historical period, and National Communications (NCs) and Nationally Determined
501 Contributions (NDCs) for the forward-looking assessment; and (ii) independent scientific
502 estimates (including estimates summarized in the IPCC AR6) of historical anthropogenic net
503 emissions and future “well-below 2°C” emission pathways. We assume that the independent
504 scientific estimates will be used as “benchmark” against which the aggregated country data
505 will be assessed to identify the “emissions gap”^{51,54,55}. Consistent with this assumption, in
506 2022 (i.e., in time to be used by the Global Stocktake) the contribution of Working Group III
507 to IPCC AR6³⁹ is expected to provide “anthropogenic emissions and removals in each of
508 agriculture, forestry, other land uses”, emissions from “non-managed terrestrial ecosystems”,
509 and “their implications for mitigation pathways”. The information on non-managed land is
510 because such lands can contribute important climate sinks and feedbacks (such as thawing of
511 permafrost⁵⁶), affecting the long-term climate goals.

512

513 We further assume that country GHG data will be extracted (and summed up at global level)
514 from the “Land Use, Land-Use Change and Forestry” (LULUCF) “reporting” of total net
515 land flux in managed lands, rather than from the “accounting”, which refers to the
516 comparison of net emissions due to mitigation actions with the agreed country mitigation
517 targets⁵⁷. For LULUCF the accounting filters flux estimates through negotiated “accounting
518 rules”, aimed to reflect only the impact of individual country’s mitigation actions¹⁵.

519 For assessing the collective progress toward the “balance” between GHG emissions and
520 removals, the Global Stocktake will require globally aggregated values of absolute net
521 anthropogenic land GHG emissions, i.e. as reported by countries for managed lands and not
522 “filtered” by “accounting rules”. For the historical period, GHG estimates will be available
523 in the NIRs submitted by each country as per Article 13.7(a) of the PA. For the forward-
524 looking assessment, these absolute values need to be extracted from the NDCs or country’s
525 projections, which may have applied specific accounting rules (SI section 1) that may affect
526 the estimated fluxes⁵. For example, a country may use a “forest reference level” (i.e., a
527 benchmark of forest net emissions expected under business-as-usual activity against which
528 the future net emissions due to mitigation activity will be compared¹⁵) to quantify the forest
529 mitigation contribution toward its 2030 NDC target. In the case where areas of managed
530 forest are already a sink and expected to still be a net sink in 2030 without any change in
531 management, the forest may not deliver “additional” mitigation in 2030 (relative to the
532 reference level). Therefore, while the forest “accounting” in the NDC may be zero, the
533 Global Stocktake will need to consider the absolute forest sink expected to be included in the
534 “reporting” for 2030. In this context, it is key for countries to provide disaggregated and
535 transparent information on how LULUCF is included in its NDC, such that the expected
536 changes in absolute values of fluxes can be extracted.

537

538 **Country data submitted to UNFCCC**

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

541 Global LULUCF country CO₂ data in Fig. 2 (1990-2014) are updated to February 2016
542 (from⁵, dashed green line), or updated to June 2018 for this study (solid green line). The
543 recent update includes new CO₂ data from the 2018 GHGIs of all UNFCCC Annex I
544 countries⁵⁸ (broadly defined in this paper as “developed countries”) and from the BURs⁵⁹
545 and NCS⁶⁰ of several Non-Annex I countries (broadly defined in this paper as “developing
546 countries”), including Brazil, China, Indonesia, and Malaysia. Note that some developing
547 country data in Fig. 2 include some non-CO₂ emissions. However, this contribution is
548 assumed to be very small, e.g., for developed countries, the non-CO₂ emissions are around 2-
549 4% of the total CO₂-equivalent forest sink⁷.

550 Our study mainly focuses on forest CO₂ fluxes of developed countries (Fig. 4), most of
551 which have a consolidated experience in GHGIs and more detailed and robust information
552 that many developing countries’ GHGIs. However, to highlight the global relevance of our
553 analysis, forest CO₂ flux estimates from developing countries are also shown in Fig. 5 for the
554 period 2005-2014. While the lack of specific forest CO₂ flux data in many developing
555 countries prevents us to provide a complete global analysis, our study is globally relevant,

556 because global data in Fig. 5 cover about 80% of the FAO-FRA’s global “secondary forest”
557 area (66% for developing countries only). The methods used to collect forest CO₂ estimates
558 from developed and developing countries (as shown in Figs. 4 and 5) are outlined below.

559 **Developed countries** (UNFCCC Annex I): The following 40 countries are included in this
560 study (Table SI 4): Australia, Belarus, Canada, EU (28 countries), Japan, Kazakhstan, New
561 Zealand, Norway, Russian Federation, Switzerland, Turkey, Ukraine and USA. The 1990-
562 2014 time series of forest CO₂ estimates used in this study (Fig. 4) are taken from the GHGIs
563 submitted in 2018⁵⁸, and include the following categories from the LULUCF sector: Forest
564 land (including “forest remaining forest” and “land converted to forest”), Harvested Wood
565 Products and forest fires. Estimates for deforestation are from “forest converted to all other
566 land uses”. Although GHGIs include all GHG, here we considered only CO₂ to allow
567 comparability with the other datasets used in this study. The main sources of non-CO₂ forest
568 emissions are forest fire (CH₄ and N₂O) and emissions associated with the loss of forest soil
569 organic matter (N₂O).

570 All developed countries use the 2006 IPCC Guidelines for estimating fluxes in their GHGIs,
571 which implies the use of the “managed land proxy” (see SI section 1), even if this concept is
572 explicit only in few GHGIs¹⁴ (e.g. US, Canada, Russia; in most EU countries all land is
573 implicitly reported as “managed”). We estimated that the impact of recent indirect
574 anthropogenic effects is included in the large majority of developed countries’ GHGIs (see
575 Table 1 and Table SI 2).

576 **Developing countries** (UNFCCC non-Annex I): data in Fig. 5 include forest CO₂ estimates
577 only, including afforestation, regrowth and forest degradation, but excluding emissions from
578 deforestation, peat fires and peat decomposition. Given the high uncertainty in the data from
579 many developing countries, we applied a number of filters. First, we considered only recent
580 (post-2014) information from BURs⁵⁹, NCs⁶⁰ and REDD+ submissions⁶¹, occasionally gap-
581 filled with FAO-FRA 2015 for forest area only (using data for “secondary” and “planted”
582 forests), see Table SI 5. Second, we used estimates only for the 2005-2014 period (where
583 only one or two data points were available, we considered this data to be representative for
584 the whole period). Third, we selected only data estimated using the 2003 IPCC Good
585 Practice Guidance or the 2006 IPCC Guidelines, for the “forest land” category of BURs or
586 NCs, or for the relevant activities of the REDD+ submissions (i.e., forest degradation,
587 conservation, sustainable management of forests and enhancement of forest carbon stocks,
588 which we considered all being part of the “forest land” category).

589 After the filters above, we were able to collect forest CO₂ flux estimates from about 50
590 developing countries, including (Table SI 5) Argentina, Brazil, Chile, China, Colombia,
591 Congo, Costa Rica, Ecuador, Ethiopia, Georgia, Ghana, India, Indonesia, Kenya, Lao,
592 Malaysia, Mexico, Mongolia, Namibia, Nepal, Papua New Guinea, Paraguay, Republic of
593 Korea, South Africa, Swaziland, Tunisia, Uganda, Uruguay, Venezuela, Vietnam (plus other
594 smaller countries).

595 The use of either 2003 or 2006 IPCC methodological guidance implies use of the “managed
596 land proxy”, even if rarely mentioned (e.g., Brazil¹⁴). Several developing countries do not
597 report unmanaged lands³¹, implicitly considering all forests managed. Due to frequent lack
598 of precise methodological information, for many developing countries it is difficult to draw
599 precise conclusions on the role of indirect anthropogenic effects on GHGI estimates.
600 Nevertheless, based on the available information (see SI section 3, Tab. SI 6, countries’
601 GHGIs and ref.³¹) we conclude that the GHG data of the most important developing
602 countries (in terms of forest CO₂ sinks or area, i.e. China, Brazil, India and Malaysia,
603 corresponding to about 70% of the forest sink of developing countries in Fig 5a) capture
604 most or all recent indirect anthropogenic effects.

605 While many developing countries report some data on LULUCF net emissions⁵, not many
606 report explicitly emissions from deforestation. An approximate estimate of emissions from
607 deforestation in developing countries for the period 2005-2014 was derived starting from
608 their total LULUCF emissions (around 2 GtCO₂/y, based on an update of ref.⁵) and then
609 subtracting their net forest CO₂ flux from GHGIs estimated above (around -1.6 GtCO₂/y
610 including “forest land” category but excluding deforestation, see Fig 5a, central green
611 column) and the emissions from peat fires and decomposition (around 0.6 GtCO₂/y, reported
612 by Indonesia). This approach simplistically assumes that net emissions from non-forest land
613 uses are negligible.

614 The values of GHGIs’ uncertainty (+/- 1 SD) in Figs. 4 and 5 are based on the information
615 reported in countries’ GHG reports, following the methodology described in the SI of ref.⁵.
616 According to this information, the uncertainty of forest-related fluxes (expressed as 95% CI,
617 and often including deforestation) is approximately 25% for developed countries and 40%
618 for developing countries. An uncertainty of 60% was assumed for all those developing
619 countries where no information on uncertainty was available. This information was then
620 converted into +/- 1 SD for this paper.

621

622 **Bookkeeping Model**

623 Houghton’s bookkeeping model was first developed more than 30 years ago⁶². It has been
624 used since then to track changes in terrestrial carbon stocks as a result of land use and land-
625 cover change (LULCC). The most recent analysis⁹ includes six types of land management
626 since 1850: conversion of native ecosystems to croplands, to pastures, and to plantation
627 forests (and the recovery of native systems following abandonment); harvest of industrial
628 wood and fuelwood; and fire management (in the USA and SE Asia). The approach does not
629 include natural disturbances. Data for annual changes in agricultural areas and harvests are
630 obtained from the FAO after 1960 and from other, varied sources between 1700 and 1960⁹.

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

636 Rates of growth and decay for 20 types of ecosystems are based on field measurements over
637 the 1970-2010 period. The rates vary among ecosystem types but are constant through time.

638 That is, rates of growth and decay are the same in 1850 as they are in 2015. That assumption
639 was an attempt to include only the effects of anthropogenic management, and to exclude the
640 effects of environmental change, e.g., CO₂ fertilization, climate, or N deposition. Using
641 those rates presumably leads to small overestimates of biomass and growth at the beginning
642 of a simulation and an underestimation towards the end of a simulation.

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

648 Data from ref.⁹ used in this study include only CO₂ emissions from the following categories:
649 Forest conversion to cropland or abandonment of cropland back to forest (FC); forest
650 conversion to pasture or abandonment of pasture back to forest (FP); forest loss that is
651 unexplained by gains in cropland and pasture and is converted to crops and then
652 subsequently abandoned back to other land in the form of regrowing forest (FCO); forest or
653 other land converted to planted forest (PLANT); industrial wood harvest (IND); fuelwood
654 harvest (FUEL); and fire emissions (FIRE, only for USA among developed countries).

655 The values of uncertainty (+/- 1 SD) in Figs. 4 and 5 are based on the values reported by ref.⁹
656 for the regions corresponding to developed and developing countries. It should be noted that
657 it was not possible to calculate the standard deviation after 1990, and the estimated values
658 for individual regions refer to the period 1950–1990⁹.

659

660 **Dynamic Global Vegetation Models (DGVMs)**

661 The IPCC Fifth Assessment Report (AR5)²¹ and the Global Carbon Project (GCP)¹⁰ assess
662 land model intercomparisons that have been coordinated by the project “Trends and drivers
663 of the regional-scale sources and sinks of carbon dioxide (TRENDY²⁴;
664 <http://dgvn.ceh.ac.uk/node/9>). The DGVMs were forced with historical data for climate,
665 atmospheric CO₂ concentration, N deposition, and land cover transitions. Some DGVMs
666 include forest management (e.g., wood harvest) in the simulations (e.g., refs.^{34,35,49}).

667 The TRENDY v4 models²⁴ were forced with a reconstruction of the land use, either the
668 HYDE dataset of cropland and pasture distributions⁶³, or the LUH-v1⁶⁴ dataset, based on
669 HYDE, but providing annual, half-degree, fractional data on land cover distribution,
670 including cropland, pasture, “primary” forests and “secondary” forests, as well as all
671 underlying transitions between land-use states, and including wood harvest and shifting
672 cultivation. The HYDE data are based on annual FAO statistics of change in agricultural
673 area⁶⁵. For the period 2011-2013, the HYDE data set was extrapolated by country for
674 pastures and cropland separately based on the trend in agricultural area over the previous 5
675 years. The HYDE data set is independent from the data set used in the bookkeeping model⁹,
676 which is based primarily on forest area change statistics. Furthermore, although LUH2-v1
677 dataset distinguishes forested and non-forested land (based on a separate underlying global
678 model⁶⁴) and indicates whether land-use changes occur on forested or non-forested land,
679 typically only the changes in agricultural areas are used by the models and are implemented
680 differently within each model (e.g., an increased cropland fraction in a grid cell can either be

681 at the expense of grassland, or forest, the latter resulting in deforestation; land cover
682 fractions of the non-agricultural land differ between models). Thus the DGVM forest area
683 and forest area change over time is not consistent with the FAO's forest area data used for
684 the bookkeeping model to calculate emissions from land-use change. Similarly, model-
685 specific assumptions are applied to convert deforested biomass or deforested area, and other
686 forest product pools, into carbon in some models.

687 DGVMs typically classify vegetation in broad plant functional types (PFT) and use average
688 characteristics of each PFT within rather coarse resolution gridcells (0.5° or coarser). Not all
689 TRENDY models simulate wood harvest or fire, and most do not simulate forest age-class
690 distributions (see Tab. SI 7).

691 In this study, we used the TRENDY data to assess the impact of indirect effects in managed
692 forest land (excluding land-use change and harvest, already captured in the bookkeeping
693 model). The model run relevant to our study is "S2" environmental change only (climate,
694 CO₂ fertilization and N deposition, but no land cover change or management). We post
695 processed the results from nine DGVMs in the framework of the TRENDY-v4 project²⁴.
696 Note that in the current version of TRENDY only the JSBACH and ISAM models provide
697 forest Net Biome Productivity (NBP) separately from other vegetation NBP, and the other
698 models give total NBP in the grid cell. For these other models, we computed the total NBP
699 per unit of area, at grid-cell level (from S2 model runs), and then assumed that forest NBP
700 equals total NBP (i.e., assume that non-forest NBP is negligible). Although this assumption
701 is crude, it is supported by several lines of evidence. At the global level, ref.²⁸ concluded that
702 "within the limits of reported uncertainty, the entire terrestrial C sink is accounted for by C
703 uptake of global established forest" and consequently, "non-forest ecosystems are
704 collectively neither a major C sink nor a major source over the two time periods that we
705 monitored". For developed countries (i.e., the main focus of our study), the analysis of
706 countries' GHGIs indicates that, when emissions associated with land-use changes are
707 excluded, forest NBP is slightly greater (by 10%) than total NBP (including "cropland",
708 "grassland", "wetland" etc.). Overall, this suggests that at large scale non-forest NBP is
709 likely to be small relative to forest NBP.

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

721 The approach above would be improved if DGVMs were to provide more disaggregated
722 outputs (NBP from primary and secondary forests in each gridcell), or if more sophisticated
723 approaches are developed to separate ex-post forest NBP from total NBP. Models that

724 explicitly include age classes and/or secondary forest could provide a more specific
725 description of LULCC transitions.

726 The ensemble used in this study includes the following nine models: ORCHIDEE⁴², OCN⁴⁴,
727 JULES⁴⁶, CLM4.5⁴¹, JSBACH⁴⁰, VISIT⁴⁵, LPJ-GUESS⁴⁷, LPJmL⁴⁸ and ISAM⁴⁹. The main
728 characteristics of these models are summarised in Tab SI 7.

729 The original runs of these models were performed at different spatial resolutions, ranging
730 from 0.5° to 1.875° (Tab SI 7). In order to be consistent with the LUH2-v2h dataset, all
731 model outputs were resampled to the 0.25°x 0.25° spatial resolution using the first order
732 conservative remapping approach⁶⁶.

733 The values of uncertainty (+/- 1 SD) in Figs. 4 and 5 are based on the values of net forest
734 flux reported by individual DGVMs.

735 When the sum of forest CO₂ fluxes from bookkeeping model and DGVMs is expressed on
736 an area basis (Figs. 4c and 5c), we used the larger secondary forest area from LUH2-v2h,
737 assuming that the smaller bookkeeping secondary forest area is already included in LUH2-
738 v2h.

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740 **Data availability.** The data that support the findings of this study are available from the
741 corresponding author, upon request.

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744 **Additional REFERENCES for the Methods section**

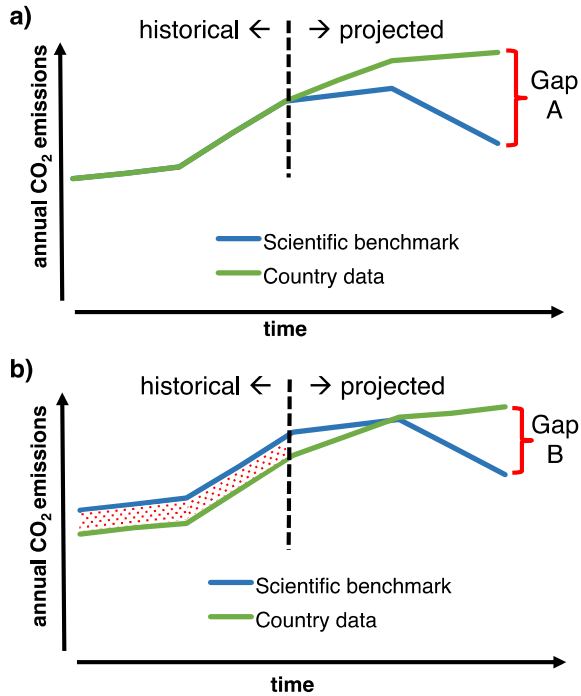
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1 **Table 1.** Processes included in each of the datasets used in our analysis: Bookkeeping model⁹,
 2 DGVMs and countries' GHGIs 2018. DGVMs include results from the TRENDY model
 3 intercomparison runs version 4 with CO₂ and climate change only (no land-use change)^{22,24} from nine
 4 models: JSBACH⁴⁰, CLM4.5⁴¹, ORCHIDEE⁴², OCN^{43,44}, VISIT⁴⁵, JULES⁴⁶, LPJ-GUESS⁴⁷,
 5 LPJmL⁴⁸, ISAM⁴⁹). See methods for details.

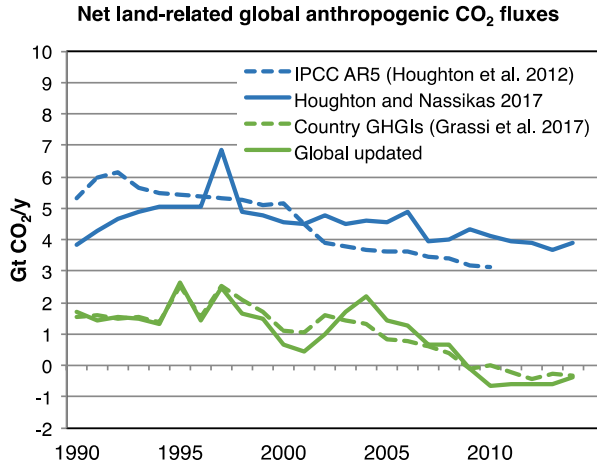
	Direct anthropogenic effects			Recent indirect anthropogenic effects on managed/secondary forests	Natural effects on managed/secondary forests	Indirect and natural effects on unmanaged/primary forest
	CO ₂ fluxes from forest land cover change	CO ₂ fluxes from harvest and regrowth	Harvested wood Products			
Bookkeeping model (1)	x	x	x			
DGVMs (CO₂ 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	

- 6 (1) This includes all forest-related C fluxes (excluding deforestation), see Methods. Blue columns in Figures 4 and 5.
 7 (2) See Table SI 6 for additional details on DGVMs. Orange columns in Figures 4 and 5.
 8 (3) Grey columns in Figures 4 and 5.
 9 (4) Green columns in Figures 4 and 5. Among the 40 developed countries analysed (UNFCCC Annex I), we estimated that
 10 the impact of recent indirect effects on forest CO₂ fluxes is partly or mostly captured in countries' GHGIs
 11 corresponding to 87% of the total forest net GHG flux and to 73% of total managed forest area reported in the GHGIs
 12 (see Table SI 2). Exceptions, i.e., where recent indirect effects are mostly not captured, are Australia, Canada, Japan and
 13 few EU countries (e.g. Czech Rep., Italy, Romania, United Kingdom). For the 50 developing countries analysed here
 14 (UNFCCC Non-Annex I), the available information suggests that the GHGIs of the most important countries in terms of
 15 forest CO₂ fluxes (i.e. Brazil, China, India and Malaysia, accounting for about 70% of the net forest sink from
 16 developing countries included in this study) capture most of recent indirect anthropogenic effects (see Methods and
 17 Table SI 2).
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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 benchmark 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 increase³⁸.



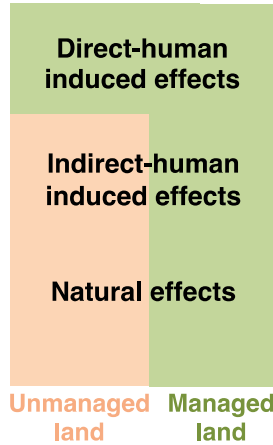
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Figure 2. Comparison of the global net anthropogenic land-related CO₂ fluxes estimated by the IPCC 5th Assessment Report (AR5) and countries' Greenhouse Gas Inventories (GHGIs). The flux in IPCC AR5 WGI table 6.1²⁰ and WGIII table 11.1²¹ was based 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 GtCO₂/y for the period 2005-2014. Positive signs indicate net emissions, negative signs indicate net removals of CO₂ from the atmosphere. See Methods for details.

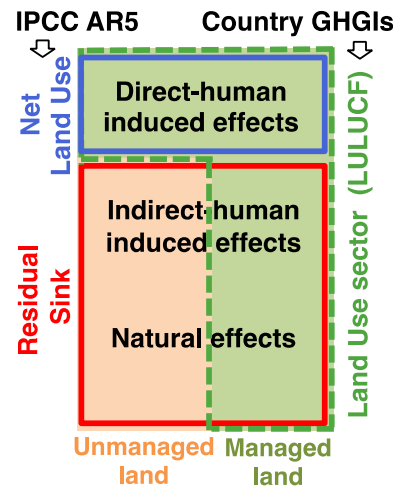
a) Effects of various factors on the forest CO₂ fluxes

- | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Direct-human induced effects</p> <ul style="list-style-type: none"> • Land use change • Harvest and other management |
| <p>Indirect-human induced effects</p> <ul style="list-style-type: none"> • Climate change induced change in T^o, precipitation, length of growing season • Atmospheric CO₂ fertilisation and N deposition, impact of air pollution • Changes in natural disturbances regime |
| <p>Natural effects</p> <ul style="list-style-type: none"> • Natural interannual variability • Natural disturbances |

b) Where these effects occur

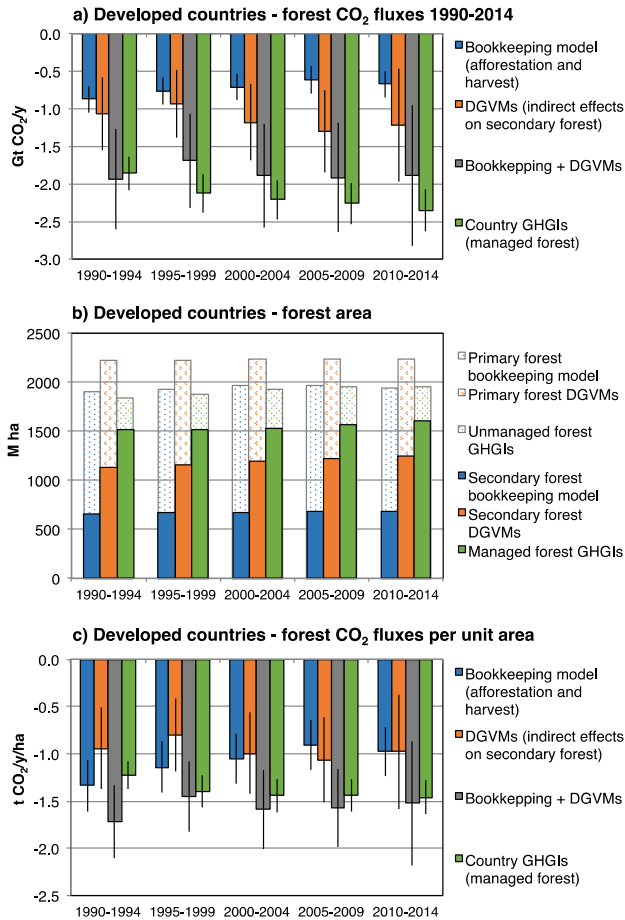


c) How these effects are captured in:



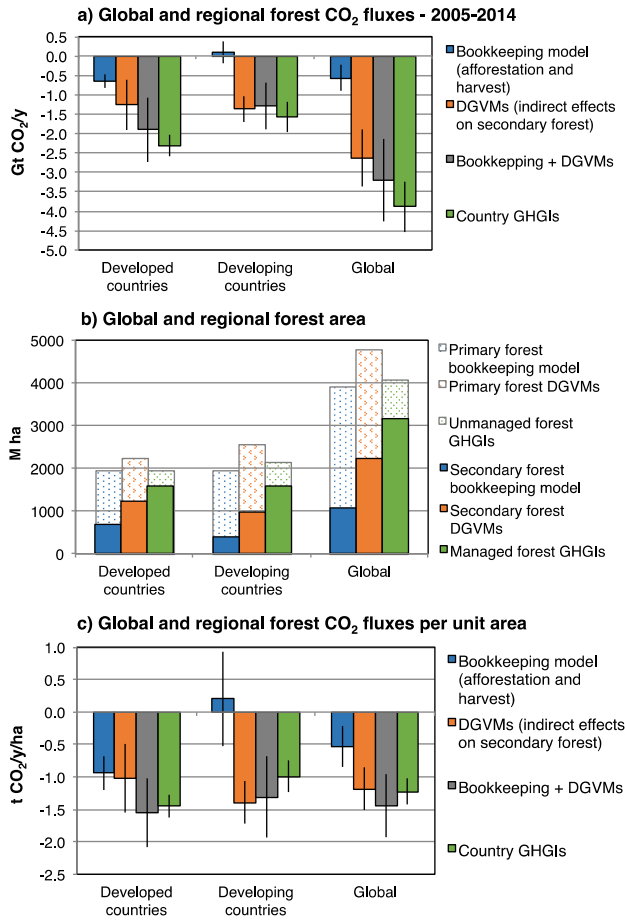
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Figure 3. Summary of the main conceptual differences in defining the “anthropogenic land CO₂ flux” between IPCC^{20,21} and countries’ GHG inventories (GHGIs). (a) Effects of key processes on the land flux as defined by IPCC¹²; (b) Where these effects 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).



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3 **Figure 4.** Comparison and reconciliation of developed countries' forest net CO₂ fluxes and forest
 4 area in the period 1990-2014 between global models and countries' GHG inventories (GHGIs). (a)
 5 Net CO₂ flux from secondary/managed forests (including afforestation, but excluding deforestation);
 6 (b) Forest area; (c) Net CO₂ fluxes from secondary/managed forests per unit area. In GHGIs,
 7 "managed forest" includes the area for which countries report net emissions to UNFCCC.
 8 "Secondary forest" (considered here conceptually comparable to "managed forest") refers to area
 9 classified as forest in the period analyzed and subject to some human disturbance in the past,
 10 according to the bookkeeping model⁹ or to the analysis of DGVMs (using the LUH2-v2h dataset, see
 11 Methods). The grey column in panel (c) (bookkeeping + DGVMs) is estimated as the grey column in
 12 panel (a) divided by the orange column only in panel (b) (secondary forest area of DGVMs), because
 13 we assume that the smaller bookkeeping secondary forest area (blue column in (b)) is already
 14 included in the DGVMs secondary forest area. Whiskers express +/- 1 SD.



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Figure 5. Comparison and reconciliation of global forest net CO₂ fluxes and forest area in the period 2005-2014 between global models and countries' GHG inventories. (a) Net CO₂ flux from secondary/managed forests (including afforestation, excluding deforestation, peat fire and peat decomposition); (b) Forest area; (c) Net CO₂ fluxes from secondary/managed forests per unit area. From bookkeeping model⁹, 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.