Altered growth conditions more than reforestation counteracted forest biomass carbon emissions 1990–2020

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Understanding the carbon (C) balance in global forest is key for climate-change mitigation. However, land use and environmental drivers affecting global forest C fluxes remain poorly quantified. Here we show, following a counterfactual modelling approach based on global Forest Resource Assessments, that in 1990–2020 deforestation is the main driver of forest C emissions, partly counteracted by increased forest growth rates under altered conditions: In the hypothetical absence of changes in forest (i) area, (ii) harvest or (iii) burnt area, global forest biomass would reverse from an actual cumulative net C source of c. 0.74 GtC to a net C sink of 26.9, 4.9 and 0.63 GtC, respectively. In contrast, (iv) without growth rate changes, cumulative emissions would be 7.4 GtC, i.e., 10 times higher. Because this sink function may be discontinued in the future due to climate-change, ending deforestation and lowering wood harvest emerge here as key climate-change mitigation strategies.

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Results and discussion

Trends in global biomass C stocks. The CRAFT model reliably reproduces the observed trends in primary and managed forest biomass C stocks (including both above-ground and below-ground biomass) in 1990–2020 with a relative root mean square error (RMSE) of 0.57% between simulated and observed biomass C stocks by the FRA at the global level. These low divergences between stock estimates result, however, in global C emissions c. 2 times lower according to the CRAFT simulations than the estimates derived from the FRA (Supplementary Table 2). Still, the CRAFT simulations corroborated the FRA observations while adding information on annual estimations of forest C stocks, rather than the 5-years interval data provided by the FRA (Fig. 1a), and dynamic annual net C emissions (Fig. 1c, d) from managed and primary forests. The five sensitivity analyses carried out on the most uncertain model inputs and assumptions (see ‘Methods’ descriptions and Supplementary Figs. 5–10) confirmed the results presented in Fig. 1: The largest deviation derived from the sensitivity analysis considering forest gross instead of net area changes results in a relative RMSE of 1.94% with global C emissions c.2.5 times higher than the FRA estimates (Supplementary Table 2). The simulations from the reference model assumptions yield the best RMSE and closest agreement with the C budgets derived from the FRA, indicating that they are the most optimal.

In line with the FRA data, we find here that the main trend is a loss of total biomass C stocks following three phases: increase in annual emissions, stagnation and slight recovery of C stocks, resulting in net C emissions from forest biomass (Fig. 1c) by 0.74 GtC or 0.03 GtC/yr between 1990 and 2020, contrasted by an opposite trend of increasing biomass density from 70 to 73 tC/ha in total forest (Fig. 1b, d). These figures are within the range of the estimated sink in forest soil and biomass of 0.1 ± 0.73 GtC/yr in 2001–2019 found by Harris et al.17. Our estimation is also consistent with that of Tubiello et al.3 of 0.11 GtC/yr net C emissions from forest ecosystems. A comparison of FRA-derived global forest C emissions with other independent estimates reported in 1990–2015 by National Greenhouse Gas Inventories (NGHGIs)—including the Russian Federation, the USA, China, Indonesia, and India—and by the United Nations Framework Convention on Climate Change for other countries (UNFCCC, 202018) yields a slight difference of c. 1%, although the UNFCCC and NGHGI’s account, by definition, only for emissions from managed land2. Further independent comparisons at the national and macro-regional levels are compiled in Supplementary Table 1 and reveal that C emissions estimated in the present study are in good agreement with other research.

Here we find that the net C emissions mostly arise from primary forests, which undergo area loss, but also biomass thickening (Fig. 1b, d). By contrast, in spite of area loss, managed forests act as C-sinks following biomass thickening (Fig. 1b, d). Increasing biomass density is therefore key to counteract net C emissions from forest biomass in 1990–2020. While both harvest rate and burnt area increase globally over the period of observation, the increased forest growth rate that we calculate with CRAFT for both primary and managed forests over 1990–2020 emerges here as the only factor explaining increased biomass density at the global level. This is in line with other research pointing to the relevance of biomass thickening for forest C sequestration19. In addition, our finding that the forest growth rate increased annually by 0.19%, 0.21%, and 0.21% from 1990 to 2020, respectively, for primary, managed and total forests of the world is consistent with Kolby Smith et al.20 who find that also net primary production (NPP) increased annually between 0.10 and 0.25% in the period 1982–2011, as well as with other modeling and remote-sensing studies documenting a global greening trend, i.e., vegetation thickening following increased vegetation growth rate21,22. Note that estimates of annual growth rate increase in 1990–2020 by the sensitivity analyses provide narrow ranges of 0.17–0.19, 0.21–0.23, and 0.20–0.22%, respectively, for primary, managed, and total forests of the world (Supplementary Table 2).

Proximate drivers of net C emissions. We develop six counterfactual scenarios23–25 in order to investigate how forest biomass density and forest biomass C stocks would evolve in the hypothetical absence of (i) changes in harvest (CF1); (ii) changes in forest growth rates (CF2); (iii) change in burnt area (CF3); (iv) change in forest area (CF4); (v) harvest (CF5); (vi) burnt area (CF6) (see “Methods” section). The comparison of observed and simulated counterfactual trends allows us to isolate and quantify the influence of these four main drivers on global forest C-stock changes at national resolution (CF1 to 4) as well as to quantify the overall effects of total wood extraction and burnt area (CF5 and 6).

At the global level, we find that loss of forest area (CF4) is the main driver of the net C emissions from forest biomass (Fig. 2a). In the absence of changes in area, global forest biomass would act as a cumulative net C sink of c. 26.9 GtC in the study period, creating a difference of 27.6 GtC between the actual and the CF4 C budget. This effect in the absence of area change, however, is a composite of an additional C sink of 30.7 in deforesting countries and an additional C source of 3.8 GtC in reforestation countries.
Changes in harvest and burnt area from 1990 to 2020 also drove net C emissions from global forest biomass as emissions drop by c. 5.7 and 1.4 GtC in the respective counterfactual scenarios, thus generating net C-sinks of c. 4.9 and 0.63 GtC (Fig. 2a). These figures are in stark contrast with the estimated total sink of c. 49.1 and 5.4 GtC that would emerge in the hypothetical absence of harvest (CF5) and burnt area (CF6; Fig. 2a), respectively. Only changes in forest growth rates counteract the net C emissions from global forest biomass (CF2; Fig. 2a). In the absence of changes in forest growth rates, global forests would act as net C source of c. 7.4 GtC in 1990–2020, i.e., c. 10 times the actually observed source. This net effect in the absence of growth rate change results from an additional source of 30.4 GtC in countries experiencing growth rate increase and an additional C sink of 23.0 GtC in countries experiencing growth rate decline.

A sensitivity analysis on the potential underestimation of C-dynamics resulting from the use of net area change data at country level (see “Methods” section and Supplementary Fig. 5) reveals that accounting for gross area changes26 instead of net area change would result in higher global C emissions estimates (4.19 GtC in the sensitivity test versus 0.74 GtC in the reference simulation) but would reveal the same patterns of forest C-dynamic drivers (Supplementary Fig. 5). However, the magnitude of the main drivers would be slightly changed with a lower effect of changes in area (C sink in the hypothetical absence of area changes reaching 20.8 GtC in the sensitivity tests versus 26.9 GtC in the reference assessment) and a higher effect of growth rate changes (C source in the hypothetical absence of growth rate changes reaching 13.1 GtC in the sensitivity tests versus 7.4 GtC in the reference assessment). Generally, the range of results derived from the five sensitivity analyses does not change the relative importance of the individual drivers in any of the scenarios (Fig. 2a, Supplementary Table 3, and Supplementary Fig. 5). However, the sensitivity analyses highlight that the uncertainty is large enough to reverse the cumulated C signal in the absence of changes in harvest (CF1), changes in burnt area (CF3), and the complete absence of burnt areas (CF6). By contrast, the signals of CF2 (no growth rate change), CF4 (no area change), and CF5 (no harvest) are larger than the uncertainty across sensitivity analyses, signaling that our findings on these drivers are most robust.

The global trends displayed in Fig. 2a, b are the combined results of diverging national forest dynamics (Fig. 2c, h). In particular, shifts in forest area (CF4) contribute to global net C emissions only in the Global South, excluding Vietnam, India, and Chile (Fig. 2f). The impacts of changes in burnt area and harvest are similarly heterogenous, with considerable effects only in some regions (e.g., Vietnam, Mozambique, Fig. 2c, e). In contrast, changes in forest growth rates are more ubiquitous, mainly positive (leading to C-sinks) for most countries, with a few notable exceptions, mainly in arid or boreal regions (e.g., India, Spain, Argentina, Canada; Fig. 2d). Possible reasons explaining the negative effect of change in forest growth rate are forest degradation, increasing drought, cloudiness, or insect outbreaks15–19. Over the period 1990–2020, the strongest harvest impacts are observed in countries with large area of managed forest and high harvest pressure, mostly located in temperate and subtropical areas (CF5; Fig. 2g), while fire impacts are strong in only a few countries (CF6; Fig. 2h).

The fact that we use here country-level data comes both with limitations and advantages. The main limitation associated with national data is that it conceals gross C fluxes in forest biomass dynamics and blurred heterogeneity in growth conditions and anthropogenic management within countries. The country-level resolution aggregates the effects of manifold, partly counteracting processes at the local level—including photosynthesis, maintenance respiration, growth respiration, as well as forest area loss and expansion—on the annual dynamic of primary and managed forest biomass. As a consequence, our optimization of the growth function actually reflects apparent national growth rates resulting from the aggregate of these processes. However, this simplification of forest ecosystem functioning is also an advantage. Our approach reproduces forest biomass dynamics very accurately, which is complementary to most process-based models aimed at depicting biological processes and their abiotic controls27 but providing a wide range of C flux estimations1 and hardly reproducing observation from inventory data1,28,29. By contrast, the strength of the modeling approach implemented here is that it...
can be run with parsimonious data availability and allows to disentangle the major drivers behind forest C-stock and flux trajectories.

**Typology of forest biomass change.** In order to identify spatial and temporal patterns of drivers in forest biomass trends, we establish a typology of the main drivers over the period 1990–2020 (Fig. 3b). The typology we established is based on the positive versus negative shift in biomass C stocks, and highlights the most important driver of this shift as assessed through the counterfactual assessment, irrespective of the relative importance of the other drivers shown in Fig. 2. However, as the early separation between increasing and decreasing biomass C stocks in the decision tree (Fig. 3b) may conceal the effect of a major driver counteracting the observed C dynamic, the typology also accounts for possible antagonistic effects by identifying cases in which the main driver of observed C-dynamics is not, in absolute terms, the most important driver (e.g., C stocks increase but the driver with

![Figure 2 Counterfactual scenarios (1990–2020) assessing the cumulative impact of: changes in harvest (CF1); changes in forest growth rate (CF2); changes in burnt area (CF3); changes in forest area (CF4); total harvest (CF5); and total fire (CF6) on C-dynamics.](https://doi.org/10.1038/s41467-021-26398-2)
the strongest absolute effect counteracts this positive budget, see also Supplementary Fig. 3). By pinpointing the major drivers of forest change at national levels, such an approach enables to identify major levers for forest conservation.

Deforestation was the dominant driver of net C emissions from forest biomass in most countries of South America and Sub-Saharan Africa, corroborating findings from the literature\(^1\)\(^{11,30,31}\) (Fig. 3a, c). The net C emissions by countries where deforestation is the most significant driver reach c. 21.3 GtC, with only 0.3 GtC of these emissions being counteracted by another major driver (either increased growth rate or lower harvest pressure). These emissions represent c. 92.7% of the 21.9 GtC net emissions arising from all countries acting as net C sources (Fig. 3c). Changes in forest growth rates act as the primary drivers in most countries experiencing a net C sink over the period (Fig. 3a, c). The net C-sinks by countries where changes in forest growth rates are the main driver reach c. 16.4 GtC, with 0.9 GtC of these sinks being counteracted by another major driver (increased harvest pressure in all cases except for Sudan where area loss was the major driver counteracting the C sink). These C-sinks mainly driven by Enhanced Growth rate represented c. 77.5% of the 21.1 GtC net sink created by all countries acting as net C-sinks (Fig. 3c).

Forest area expansion from 1990 to 2020 is the main driver of forest biomass net C sink in only a few Northern countries but...
also some Southern countries, namely Vietnam, India, and Chile, in line with findings reported for these countries, all together accounting for a net C sink of 3.9 GtC. However, more than half of the C-sinks mainly driven by reforestation are counteracted by another major driver (either declining forest biomass growth rate or increased harvest pressure). Similarly, changes in harvest as well as changes in burnt areas are the main drivers of net C sink or source for a handful of countries in 1990–2020 (Fig. 3a). Finally, declining forest biomass growth rate is the primary driver of net C emissions only in Mongolia and Canada, which is consistent with other studies highlighting slower growth, higher mortality, and insect outbreak events in Canadian forests.

These highlights derived from the typology remained the same in all sensitivity analyses (Supplementary Figs. 6–7), despite some possible changes in country type identification (Fig. 3a and Supplementary Fig. S6) and amplitude shifts in the attribution of main drivers globally (Fig. 3c and Supplementary Fig. 7). The ranges of values in the attribution of main drivers result from the previously reported differences between the counterfactual and actual C budget estimates across sensitivity analyses (see Supplementary Tables 2–3) combined with some changes in the type of forest C-dynamics trajectory identified through the typology in countries with large forest biomass stocks: China, India, and Australia (Supplementary Note 1 and Supplementary Fig. 6). However, these shifts do not affect the main conclusions derived from Fig. 3c: in all sensitivity analyses, growth rate changes remain the main driver of global forest biomass C sink with total net C-sinks in countries where increasing growth rate is the main driver (including both solid and hatched countries) ranging from 12.1 to 21.1 GtC, while afforestation always holds the second place of global C sink driver (total net C-sinks in countries where afforestation is the main driver ranging from 2.4 to 7.7 GtC). Similarly, total net C sources by countries where deforestation is the main driver range from −21.9 to −14.0 GtC, thus highlighting that deforestation would by far remain the main driver of forest biomass C emissions across all sensitivity analyses.

Implications for forest-based solutions. Our results allow to identify major mechanisms behind observed forest biomass C changes that are immediately relevant for forest-based climate-change-mitigation strategies. We show that deforestation, increasing harvest, and burnt area have driven the net C emissions from forest biomass over the last three decades. Deforestation is the dominant driver, corroborating that protection from deforestation is indispensable. On the other hand, forest growth rate is identified as the major driver counteracting net C emissions (Fig. 2a, d). In fact, most of the temperate and boreal countries, with the noteworthy exception of Canada, fall under a type in which enhanced forest growth rate is the major driver of a net C sink (Fig. 3b). Besides, even countries dominated by deforestation in the tropics show significant increases in growth rate (Figs. 2d and 4). These results highlight that enhanced growth rate, rather than reforestation, is the main driver counteracting biomass C emissions in 1990–2020.

These increases in forest growth rate may arise from diverse processes, including climatic and land-use drivers. On the one hand, several studies highlight the effects of environmental drivers—such as warming, atmospheric carbon dioxide (CO2), and nitrogen (N) fertilization—on the terrestrial C sink. On the other hand, changes in forest growth rate can also be driven by shifts in forest management practices, such as tree species selection, forest recovery from past degradation and lesser litter grazing. Advancing the understanding of the underlying processes of forest growth rate change is key for forging climate-change-mitigation strategies, but it is not straightforward to isolate climatic (e.g., altered CO2 concentration or temperature) from land-use drivers (e.g., non-timber forest uses such as grazing). Still, a comparison of trajectories in primary and managed forest growth rate change based on our results allows to derive insights into the interplay of these different drivers (Fig. 4 and Supplementary Fig. 3). From the fact that only 11% of primary forest carbon stocks show declining growth rate trends (Fig. 4c) while a relatively larger carbon stock in managed forest (22%) is affected by declining growth rate trends (Fig. 4b), we can infer that in overall terms—and assuming primary and managed forests of a given country to be similarly affected by climatic drivers —land use is likely to exert a degrading effect on growth rate dynamics. Nevertheless, some countries reveal declining growth rate in primary forest but increasing growth rate in managed forest, thus suggesting that forest management may have an improving effect on forest growth rate in those countries (e.g., USA, Fig. 4b, c, see also Supplementary Fig. 4). In overall terms, this result suggests that globally a reduction of forest use may have the potential to enhance growth rate, thus corroborating previous findings by Quesada et al. However, these interpretations warrant a caveat that primary versus managed forest growth rate changes are derived from the FRA data and a state-of-the-art of the literature on changes in primary forest density (see “Methods” section and Supplementary Note 2), the latter being associated with higher uncertainties although the corresponding sensitivity analysis testing suggests these uncertainties to have little impact on the figures displayed here (see Supplementary Tables 2–3 and Supplementary Figs. 5–10).

Independent of their origin (management or climate driven), the future trajectories of this driver, forest growth rate, is subject to large uncertainties. Research suggests that increasing forest growth rate is a transient phenomenon and might be discontinued in the future. For instance, several recent studies have pointed toward the saturating effect of CO2 fertilization, which is suspected to be a key process underlying vegetation greening and ensuing thickening, the risk of increasing mortality and slower growth rate following increasing drought, temperature, and natural disturbances such as insect outbreaks. Even more recently, Duffy et al. showed that, in the near-future, temperature increases from business-as-usual trajectories of climate change shall result in a severe reduction, and possibly a reversal, of the terrestrial C sink, despite the remaining unknowns.

Therefore, we conclude that, while increasing forest growth rate is the dominant driver counteracting the global net C emissions from forest biomass in the past three decades, it is against a precautionary principle to forge climate strategies that rely on a continuous net C sink effect from the same processes in the future. By contrast, our results suggest that reducing wood harvest (Fig. 2g) and halting deforestation (Fig. 2c) are key strategies to address the challenge of climate-change mitigation. In this context, increasing forest harvest volumes—a strategy often promoted in the course of climate-change-mitigation efforts embraced as the “bioeconomy”—appears to have critical unintended side-effects, despite the potential of wood for substituting some emissions-intensive products and processes by not only reducing the carbon sink function in forests, but also accelerating the overall C turnover rates through rejuvenation of forests and transfer to harvested wood products of lifetimes shorter than those of old-growth forests. Such strategies result in a critical loss of C sink capacity. Overall, our results plead for a double strategy to enable future forest-based solutions for climate-change mitigation: in the Global South, ending deforestation is the main priority to reverse the net C source toward a net C sink, while in the Global North, lowering wood harvest has the strongest potential to immediately enhance the C sink in forest biomass.
The input data to simulate C-stock and et al.59. The calibration data are the observed data of standing biomass of primary losses at cutting, which were taken as 4% and 11%, respectively, based on Liski main (tC), extent of burnt area (Mha), primary, and managed forest area (Mha). The tested at the national level by steps of 0.01 yr

The cumulated size of the carbon stock in 1990 (nC) – axis). The area between the graph and the x-axis indicates the C-stock change due to growth rate for total (a), primary (b), and managed forests (c) (see Supplementary Figs. 8-10 for results from sensitivity analyses).

**Methods**

**Principles of the CRAFT model.** CaRbon Accumulation in Forests (CRAFT) is a parsimonious model of long-term changes in carbon (C) stocks and fluxes in forest ecosystems16. CRAFT builds upon the establishment of a place and time-specific relationship between NPP and biomass C stocks and so provides a suitable tool to simulate C-stock dynamics in forest biomass and soils (including both above-ground and belowground biomass). In the present paper, only the biomass module was applied at the national level, distinguishing two key forest categories: primary and managed forest (see definition of the primary versus managed forest below).

The input data to simulate C-stock and flux dynamics in biomass are wood harvest (tC), extent of burnt area (Mha), primary, and managed forest area (Mha). The main fixed parameters of the CRAFT model are the mortality rate and the % of losses at cutting, which were taken as 4% and 11%, respectively, based on Liski et al.19. The calibration data are the observed data of standing biomass of primary and managed forest at the national level (MtC). From these input and calibration data, we calculated forest growth rate values of 0.07, 0.10, and 0.21% until 2020, respectively, for primary, managed, and total forests.

**Range of growth parameter values.** To derive a range of possible values for the forest growth parameters, we relied on-site measurement data on standing biomass and NPP from all ecozones of the world, compiled by Cannell82, Luyssaert et al.8, and Anderson-Teixeira et al.84, contributing 372, 503, and 536 data points, respectively (see Supplementary Table 4). The expansion factors, i.e., the allometric coefficients between tree stems and other tree parts, per ecoregion given in Supplementary Table 5, were tree organs. Equation (1) was fitted to best reproduce the site measurements in each ecoregion. The r and K parameters of the curve with the smallest residues to the data points were identified (using the MATLAB function fmincon), under the constraints of r being between 0.01 and 1.00, and K being between 0 and 1000. The agreement of fit for the fitted function was calculated. To arrive at a range of r and K values, data were only selectively used for the fitting of the function. For the minimum values of r and K, only NPP values below the median were used per 0.2 percentile of biomass values. For the maximum values of r and K, only NPP values above the median were used per 0.2 percentile of standing biomass.

**Optimization of growth parameter values.** These optimizations were performed with a routine using Macros in Microsoft Excel so that simulated data best fit the available observed data within the CRAFT model. At the global level, we calculated forest growth rate values of 0.07, 0.10, and 0.09 yr⁻¹ in 1990 and estimated that these values increased annually by 0.19%, 0.21%, and 0.21% until 2020, respectively, for primary, managed, and total forests of the world.
biomass values. Using this approach, we were able to derive a range of values for the \( r \) and \( K \) parameters from 0.03 to 0.21 yr\(^{-1} \) and from 100 to 720 tC ha\(^{-1} \), the lower and upper degree of the fitted curve. We used these ranges of values for all countries of the world to optimize nationwide growth parameters for both primary and managed forests (see section above).

**Input data forest area.** Data on forest area were extracted from the last Forest Resource Assessment (FRA) (https://fra-data.fao.org/), which distinguishes between primary forest (‘mangrove’, ‘planted forest’, and ‘naturally regenerated forest’). As mangrove can be both primary and managed forest (FRA\(^3\)), we calculated the primary forest area as the sum of the ‘primary forest’ area and half of the ‘mangrove’ area reported by the FRA. As the mangrove area is generally very small in comparison with primary forest area, this assumption does not significantly influence our simulations. The managed forests, i.e., the forests exploited for socio-economic activities, are taken as the total forest area reported by the FRA minus our estimations of primary forest areas.

**Input data harvest.** Wood harvest data were extracted from FAOstat (http://www.fao.org/faostat/en/). We extracted data for eight wood categories: wood fuel, pulpwood, sawlogs, and veneers logs, other industrial roundwood for both coniferous and deciduous wood (provided in m\(^3\)). To convert wood extraction from m\(^3\) to tC, we used coefficients on wood density (t m\(^{-3}\)), bark fraction (bark wood\(^{-1}\)), and C content (tC wood\(^{-1}\)). These coefficients were specific to product and countries following Haberl et al.\(^{65}\). We then summed all wood product harvest at the country level to have an aggregated value of annual wood harvest (tC yr\(^{-1}\)). As the FRA provided wood extraction data only from 1990 to 2019, we assumed the same harvest figures in 2020 as in 2019.

**Input data on burnt area and fire losses.** Data on forest area burnt were extracted from the last FRA (https://fra-data.fao.org/). From this data, we calculated the annual live tree biomass loss by fire such as:

\[
\text{FL} = \left( C_x B_x + C_y B_y + C_z B_z \right) \times \text{AFI} \times \text{CtC} = (A_{\text{fi}} A_{\text{re}}) B
\]

With FL the annual loss by fire (tC/yr); C the fraction of the respective tree compartment (i.e., wood, i.e., branches and stem; \( 1 = \text{leaves} \); FFI the respective fuel load, i.e., the % of live biomass that can actually burn per tree compartment; \( \alpha \); the combustion efficiency coefficient, i.e., the % of fuel load consumed by fire per tree compartment in an area affected by fire; \( A_{\text{fi}}/A_{\text{re}} \), the fraction of area burnt over the total forest area and B the standing biomass (tC). We assumed that the fraction of area burnt was the same in managed forests as in total country distributions.

Since our study is focused on C in living tree biomass alone, we used stem and foliage as a proxy for living tree biomass, instead of calculating total forest fuels, i.e., managed and primary forest as in total country-level forest. We assumed that the fraction of area burnt was the same in managed forests as in total country distributions. In the present study, we thus calculated the managed versus primary forest biomass C stocks by using the benchmark values of primary forest biomass density provided by Erb et al.\(^{13}\) for the year 2000 at the country level. From this data, we could calculate the biomass C stocks in both primary and managed forest in 2000 such as:

\[
B_{\text{prim},2000} = BD_{\text{prim},2000} \times A_{\text{prim},2000}
\]

**Data uncertainties.** Eighteen countries reported poor data, i.e., incomplete data series or no data regarding forest area, biomass C stocks, extent of fire area or harvest. These countries are Afghanistan, Albania, United Arab Emirates, Azerbaijan, Benin, Central African Republic, Chad, China, Côte d’Ivoire, Democratic Republic of the Congo, Croatia, Fiji, India, Indonesia, Iran, Lebanon, Laos, Maldives, and Myanmar. For all other countries, we use the data from the extent of area burnt as provided by the FRA without applying correction.

**Calibration data: C stocks in managed and primary forest.** Calibration data on standing biomass C stocks (including both above-ground and belowground biomass) were extracted from the last FRA (https://fra-data.fao.org/). Conversely to the forest area, the FRA did not provide data on biomass C stocks distinguishing between primary and managed forest but only for total forest biomass C stocks at the country level. In the present study, we thus calculated the managed versus primary forest biomass C stocks by using the benchmark values of primary forest biomass density provided by Erb et al.\(^{13}\) for the year 2000 at the country level. From this data, we could calculate the biomass C stocks in both primary and managed forest in 2000 such as:

\[
B_{\text{prim},2000} = BD_{\text{prim},2000} \times A_{\text{prim},2000}
\]

**Counterfactual scenario analysis.** In order to isolate and quantify the relative impacts of major proximate drivers on forest biomass C change, we develop six counterfactual scenarios\(^{23–25,75}\). In these counterfactual scenarios we investigate how forest biomass density and forest biomass C stocks would evolve in the hypothetical absence of (i) change in harvest (assuming initial average harvest volumes to remain constant; CF1); (ii) change in forest growth rate (calculated values for 1990 remain constant; CF2); (iii) change in area burnt (average values for 2000 to 2003 are assumed to remain constant; note that FRA does not report burnt area before 2000; CF3); (iv) change in forest area (values for 1990 remain constant; CF4); (v) harvest (no-harvest counterfactual; CF5); (vi) fire occurrence (no forest area counterfactual; CF6). The comparison of observed and simulated trends allows to isolate and quantify the influence of the four main drivers on the global C-stock changes at national resolution (CF1 to 4) as well as to quantify the overall effects of total wood extraction and fire occurrence (CF5 and 6).
Sensitivity analyses. The robustness of the model was assessed through five sensitivity analyses carried out on the most uncertain parameters and assumptions of the model: (i) temporal change in K parameter assumption; (ii) changes in primary forest biomass density assumption; (iii) high fire impact assumption; (iv) low fire impact assumption; (v) effect of gross versus net area changes. As the CRAFT model reproduces the observed trends in forest biomass C stocks, its highest uncertainties lie in the estimation of the growth parameters. Here, two structural hypotheses of the model are likely to affect these calculations: (i) the assumption regarding the optimization of temporal changes in growth parameters, and (ii) the coefficient derived to estimate the temporal trend in primary forest biomass density. To assess the uncertainties associated with those assumptions, we ran 2 sensitivity analyses: (i) We tested an alternative hypothesis in which both the temporal trend of the r and K parameters were optimized against the reference assumption based on the optimization of the temporal change of the r parameter only. (ii) We tested an alternative hypothesis in which biomass density in primary forest was taken as constant (using the benchmark provided in 2000 by Erb et al.15) against the reference assumption based on an estimation of changes in primary forest biomass density. Here, two sensitivity analyses and the default model assumptions are presented in Supplementary Tables 2–3 and Supplementary figures 5–10.

Data availability
All the data generated in this study are provided in the Source data file 1. Source data are provided with this paper.

Code availability
The code used to optimize the CRAFT model is provided in the macro included within Source data file 1. Click ‘View’ in the excel file then click ‘Macro’ and then ‘Edit’ to see the code.

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