Supplementary Information

The enduring world forest carbon sink

Yude Pan, Richard A Birdsey, Oliver L Phillips, Richard A Houghton, Jingyun Fang, Pekka E Kauppi, Heather Keith, Werner A Kurz, Akihiko Ito, Simon L Lewis, Gert-Jan Nabuurs, Anatoly Shvidenko, Shoji Hashimoto, Bas Lerink, Dmitry Schepaschenko, Andrea Castanho, Daniel Murdiyarso

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Supplementary Information

Definitions of forest, C pools, stock, and flux

Forest – Land spanning more than 0.5 hectares with trees taller than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*[15]. Tree plantations are included. Forest lands that are temporarily treeless because of harvest or disturbance are included. Forest does not include land that is predominantly under agricultural or urban land use, even though such land may have some tree cover.

Living biomass – includes above- and below-ground biomass of live plants. The aboveground biomass includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. The below-ground biomass includes all biomass of live roots. Fine roots of less than 2 mm diameter are often excluded or may be included with litter and soil carbon (C) pools. Understory plants may be included or excluded in cases where they comprise a very small proportion of the total biomass, as long as this is done consistently over time.

Dead wood – Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter, unless another threshold is used by the country.

Litter – Includes all non-living biomass with a diameter less than a minimum diameter, typically 10 cm, and lying dead biomass in various stages of decomposition above the mineral or organic soil. Includes the litter, fumic, and humic layers. Live fine roots may be included if excluded from living biomass in some data sources due to regionally different estimation approaches, but are consistent over time within a dataset.

Soil organic matter – Includes organic carbon in mineral and organic soils (including peat) to a specified depth of 1 meter although some data are derived from a depth of 30 cm. Live fine roots may be included if excluded from living biomass in some data sources due to regionally different estimation approaches. Different approaches are consistent over time within datasets.

Carbon in harvested wood (harvested wood products, HWP) – includes products in use and in landfills. "Products in use" includes end-use products that have not been discarded or otherwise destroyed. Examples include residential and nonresidential construction, wooden containers, and paper products. "Products in landfills" includes discarded wood and paper placed in landfills where most carbon is stored long-term and only a small portion of the material is assumed to degrade, at a slow rate. Generally, carbon in HWP is a relatively small proportion of the carbon in harvested roundwood. To the extent that the amount of stored HWP increases, we add that quantity to the estimated change in C stock[15]. However, we do not attempt to estimate the total amount stored, only the change.

We did not include a full accounting for soil carbon in forested wetlands and peatlands in this study although this large pool will be increasingly important as both sink and source of GHG[42] especially with the dynamic land-use in the tropics. Globally tropical peatlands and mangroves may store as much as 110 PgC, which have much longer residence times than upland soils but sensitive to land-use changes and should be given more consideration in the future work.

Uncertainty evaluation and major sources of uncertainty

We acknowledge that there are inherent differences in field methods and sampling in forest inventories between countries, thus it's critically important to follow valid statistical approaches in data collection and when scaling up site data to regional or country levels. The methods used for calculating uncertainties of estimates generally follow standard approaches (like from FAO and IPCC) in combinations that are attuned to country-specific circumstances.

<u>Errors in Statistical Data</u>

Evaluation of errors in statistical data is commonly associated with national forest inventories based on sampling and models. Tree and forest measurements are made at sample plots randomly located across the landscape, typically at large numbers of sampling locations. Models are necessary to convert variables that are easily measured such as tree diameter, to estimates of variables that are difficult to measure directly, like tree biomass. The approach examines probabilities that estimates are different from the "true" value where inferences can be made about the population from the sample data and model estimates. When multiple variables are used to compile an estimate, such as ecosystem carbon stock, error propagation is used to combine the individual error estimates.

Monte Carlo approach

The Monte Carlo approach is a form of error propagation, often associated with complex modeling[43]. The approach uses a selection of random values from within individual probability density functions to calculate the value of a variable of interest. The calculation is run numerous times using different selections of random variables to develop the overall probability density function of an estimate. The distribution of the calculated estimate illustrates the imprecision of the data.

Expert judgement

When quantitative estimates of uncertainties were not available from source data or could not be calculated, we derived them from expert opinion using an uncertainty scale[44]:

(1) 95% certain that the actual value is within 10% of the estimate reported

(2) 95% certain that the estimate is within 25%

(3) 95% certain that the estimate is within 50%

(4) 95% certain that the estimate is within 75%

(5) 95% certain that the estimate is within 100%

These are informed categorizations, reflecting expert judgment, using all known descriptions of uncertainty surrounding the "best available" or "most likely" estimate. For instance, for different forest components, uncertainty of C estimation in living biomass is much less than in deadwood, litter, and soils. If multiple expert opinions were available, we used the highest uncertainty among them. In addition, we considered relationships between different carbon variables: we first estimated an uncertainty scale for carbon stock changes based on data or "expert opinions". Then we used 50% of the scale to evaluate uncertainty of C stocks with an assumption that uncertainty for estimating C stock changes (the difference between stocks at two points in time) is the sum of uncertainties of stocks.

Uncertainties from data of forest area

Forest area estimates from countries with forest inventories are generally accurate (reported estimate within 5% of the true value) and sum to the estimated net change between reporting years, calculated as the difference between successive estimates. However, it is often difficult to estimate the underlying gross changes in area – i.e., afforestation and deforestation – because these estimates tend to be a small percentage of the total forest area and therefore require intense sampling methods and consistent remote sensing techniques that may not be deployed over time. Remote sensing-based estimates could underestimate forest areas for "forest land remaining forest land" by excluding harvested and other disturbed areas which are recovering before they have regenerated sufficient canopy leaf area, typically crossing a 10% threshold of tree cover.

For regions lacking forest inventories, mainly in the tropics, there are well-known problems with reported area estimates particularly regarding temporal consistency, and for some regions and countries, data on area are simply not reported in a way that is consistent with the FAO Forest Resources Assessment. Area estimates from tropical countries were based on remote sensing or sample surveys, or subjective expert assessment[45,46]. Updating older data, a common practice, also produces errors, as does re-estimating data for older reporting years if methods or definitions change. The separation of total tropical forest area by region into intact and regrowth forests is especially ambiguous with respect to accounting for small-scale selective logging because these activities are difficult to detect from remote sensing, and to evaluate their impact on either intact forests or forest regrowth, which by definition includes recovery from large-scale logging. In addition, tropical intact forests include some well-established secondary forests that have not been severely disturbed recently by human activities, which adds more uncertainty due to definition criteria. The FAO statistics include countries' data partitioned into primary and secondary forest lands, but it is difficult to know how these numbers were produced. For instance, for Amazon tropical forests, FAO reports that two thirds of forests were secondary forests[15], which does not appear realistic given that large remote areas of forests experience limited impact from human encroachment. Therefore, we did not use FAO's primary and secondary forests for defining tropical intact and regrowth forests. Instead, we used alternate sources or methods as described below for individual countries or regions.

FAO often assumes that forest remaining forests have a neutral C balance, which is why FAO provides a much smaller carbon sink than the national inventories analyzed by Grassi et al.[47], who pointed out this critical issue. For countries lacking reports of credible data on C stocks and fluxes, we use alternate sources for this information from research studies involving extensive ground measurements, depending on the country and what other sources are available.

Uncertainties from estimates of C stocks and C stock changes

Generally, estimates of C stocks and stock changes for temperate and boreal forests have lower uncertainty than estimates for intact or tropical regrowth forests because they are based on unbiased statistical sample surveys of all forest types and conditions. Also, estimates of above-ground biomass C stocks and changes in C stocks have lower uncertainty and more consistent results even with different estimation approaches, compared with greater uncertainty and inconsistency in both data and methods for estimating dead wood, litter, soil, and harvested wood C stocks and changes in these stocks.

Testing statistical significance of decadal trends in the global carbon sink

Although decadal global forest C sinks appear to decline slightly (Table 1), we applied two statistical methods to test for a significant trend. First, our null hypothesis H_0: $\mu = 0$, where μ represents a slope, decadal C sinks are treated as the same subject on continuous time. Monte-Carlo simulations were used to generate random samples for populations of carbon sink in 1990s, 2000s and 2010s, respectively, using the mean value and standard deviation of each decadal sink with 1000 repetitions. We ran a linear regression on the three observations from random simulation data, repeating it 1000 times:

$$Sink_{ij} = b_{0j} + b_{1j}T_i$$

Where, $Sink_i$ represents decadal annual C sinks, which are treated as the same subject on continuous time; i= 1,2, 3 and T_i uses 1, 2, 3 for the decade of 1990s, 2000s and 2010s to form a time series; b_{0j} is the intercept, b_{1j} is the slope of the regression, and j represents a group of random samples derived from three populations. The slope b_{1j} constructs Monte-Carlo confidence interval at significant level α = 0.05 (Fig. S1). As the confidence interval of b_{1j} includes 0, their values are not significantly different from zero. In addition, the t-test value

(0.805) for the slope of the regression is smaller than the t-criteria (2.353), we failed to reject the null hypothesis.

We further applied Cohen's *d*– an effect size (ES) of the standardized difference between two means for examining the maximum likelihood of difference between a pair of global C sinks:

$$Cohen's\ d = (\mu_1 - \mu_2)/\sqrt{{s_1}^2 + {s_2}^2},$$

where μ is a mean of global C sink and s is a standard deviation of the simulated random data. The criteria for ES have scales from 0.01 to 2.0, and when ES <0.2, as is the case for our data, the maximum likelihood of difference between compared means is unlikely significant (Fig. S1).

Specific methods used for each country or region

Methods used for each country or region are described in detail here and summarized in Table S1. In general, countries of the temperate zone have established forest inventories that provide a sound basis for estimating C stocks and changes in C stocks. Countries of the boreal zone typically have inventories for forest areas that are intensively managed for timber production or other services, and use remote sensing or models to supplement the inventory data for reporting to FAO or the United Nations Framework Convention on Climate Change (UNFCCC). In the tropics, few countries have established forest inventories, while many countries report to FAO and UNFCCC based on international databases of remotely-sensed forest land areas combined with some regional studies and measurements, or default emission and removal factors from IPCC. In the tropics, area estimates reported to FAO provide the most spatially and temporally consistent source for information about the extent of total forest land, even though there have been methodological changes over the years, and reports from some countries are considered inaccurate.

<u>Russia</u>

An earlier estimate[35] used the Russian national definition of forest which differs from the FAO FRA definition (e.g. 20% tree stocking threshold vs. 10%). The current analysis follows the FAO FRA definition and includes the relevant classes of the Russian forest land classification: main forest forming species, unstocked young planted forests, sparse forests (in part, which corresponds to the FAO definition), burnt areas (after stand replacing fire), dead stands (forest, killed by other than fire disturbances, typically by insects, pathogens or unfavorable weather condition), and unregenerated harvested areas.

The current situation for official data on Russian forests is that there are serious concerns regarding their reliability. Thus, two basic sources of forest information - the State Forest Register (SFR, from 2007 – a successor of the State Forest Account, SFA) and the State Forest Inventory (SFI, the first cycle was provided in 2007-2020) report substantial differences in the basic forest characteristics[4,48]. Data of the SFR are obsolete and biased: about half of the forest area of the country was last inventoried more than 30 years ago[49]. The last official Russia report for global FRA-2020[15] used the obsolete data of the SFR, but the problems with those data hinder the direct use of the SFR in this study. Meanwhile, detailed results of the first cycle of the new SFI are not yet published and still require quality control and analysis. Several independent remote sensing estimates of growing stock volume (GSV) dating back to the second half of the 2010s have yielded results ranging from ~94 to 111 billion m[48,50,51], but remote sensing does not assess some indicators of forests, or does not provide the necessary accuracy, for variables that are important for assessing the carbon budget of forests.

For forest area estimates we therefore used a framework based on satellite data at spatial resolution ~150 m, integrated with an expert system of up-to-date Russian forest inventory data which were developed for every nation-wide forestry enterprise (in total c. 1600) for 2009-2019, including both appropriately updated forest inventory information and regional models[5]. An exception was made for area estimates for 1990 which were derived from official inventory data reported in the SFA[52,53,54]. For some indicators (particularly of zonal ecotones and sparse forested areas of high latitudes), high spatial resolution remote products and updated SFA/SFR data were used[4,55].

For GSV estimates in 1990-1999, we based our analysis on official data of the SFA for 1978-2003. These data have been corrected to eliminate biases of different methods of forest inventory which were applied in the country over the last three decades[1,2]. The GSV data for 2000, 2010 and 2020 were assessed by the integration approach including control comparisons of independent estimates for individual years and the expert system mentioned above. Live biomass and dead wood (coarse woody debris) were assessed based on new systems of regional multi-dimensional biomass expansion factors, which include all structural components of forest ecosystems, not only trees[3,56].

For estimating carbon in harvested wood, we based our analysis on official statistics which report wood removal in units of commercial wood volume. These data were recalculated in units of harvested GSV, then converted to carbon. All types of harvest are included, not only final felling, but thinning and sanitary cuts. Illegal harvest was not included. Wood in landslides was not included due to lack of data.

Soil carbon estimates are based on the latest assessment for 2014[57]. Estimates for other years that lacked inventory data are based on empirical models that link soil C dynamics during the considered decades with the amount of input of organic matter, basically in form of dead roots due to natural mortality, harvest and natural disturbances, particularly fire and biogenic agents, live biomass and level of disturbances, and the output due to decomposition of the organic matter and transport to the hydrosphere. The 2000-2019 periods had substantial acceleration of the disturbance regimes in Russian forests. A substantial increase of SOC in litter was observed on abandoned arable land – 25 M ha of which were transformed into forests[58]. The estimates for soil C include the organic layer above the soil and the 1m top layer below the organic layer (litter) of mineral soils, and 1m depth for the organic soil (peat). The average results per unit of area are in the range of reported estimates for Nordic countries[59,60,61]. Estimates of uncertainty were provided by error propagation with some elements of expert estimation, basically for 1990-1999. Application of the FAO definition results in the carbon sink estimate to be approximately 20% lower than assessments which use the Russian national definition in the stock-based method as well as in the absolute majority of modelling application of flux-based (gain-loss) methods[4].

Canada

Estimates of C stocks and C stock changes were obtained from Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS)[62] which was developed to meet international reporting requirements for greenhouse gas emissions and removals in Canada's managed forest. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)[63] is the core model of NFCMARS. Details of data sources and regional results are provided elsewhere[7]. Data for Canada include both the anthropogenic and the natural disturbance categories reported for Canada's managed forest. Because of data limitations, estimates of C stocks and stock changes are limited to the 226 Mha of managed forest, leaving unaccounted some 121 Mha of northern forests that are not subject to management (Table S6). Information on deforestation rates is derived from a national deforestation monitoring program implemented for all of Canada's managed and unmanaged forests to meet the reporting requirements of the UNFCCC.

The CBM-CFS3 is a well-established C budget model used in Canada and internationally[64]. It relies heavily on empirical data on forest conditions and forest changes, and simulates C stocks and stock changes in dead wood, litter and soil C as mass balances calculated from inputs (through litterfall, biomass turnover and disturbance inputs) and losses (through decomposition, transfers by harvesting, and losses to the atmosphere during disturbances such as fire)[62,63,64,65]. Following the recommendations of the IPCC, the model links dynamics of dead organic matter pools directly to the dynamics of the better-known biomass dynamics. At present, the CBM-CFS3 does not account for C stocks in forested wetlands with deep (peat) organic soils whose dynamics are strongly affected by water table fluctuations for which few data exist at the national scale. Estimates of harvested wood product (HWP) C are derived from a comprehensive harvested wood products model that simulates wood harvest in Canada from 1900 to 1989 at the national scale (to initialize HWP pools) and from 1990 to 2020 at the scale of Provinces and Territories[8]. Estimates are based on the "production approach", which accounts for HWP derived from wood produced in Canada, regardless of where the wood products are consumed. HWP transfers to landfills are assumed to be instantly oxidized and Canada does not report HWP storage in landfills.

<u>Interior Alaska</u>

Three categories of forest land in Alaska are used in our analysis: the Southeast part (4.2 million ha), included with the temperate zone data for the United States; the "managed" part (24.5 million ha) of Alaska's interior, reported in the boreal zone; and the "unmanaged" part (8.2 million ha) of Alaska's interior, which is not reported because of lack of data. The methods used for Alaska are those used for the U.S. greenhouse inventory as that is the source for all reported data[12]. For the temperate part of Alaska, refer to the methods described later for the temperate part of the U.S. as they are also relevant for temperate Alaskan forests. There are some differences in methods used for the managed part of Alaska's interior, so those are briefly described here.

The area of managed and unmanaged forest for Alaska, and the classification of sample plots, is based on National Landcover Data (NLCD) since higher-resolution area data were not available. Areas of managed and unmanaged forests for Alaska are described and mapped in Ogle et al.[66].

Forest carbon stock and stock-change estimates for Alaska's interior are based on national forest inventory (NFI) sample plots, except that there are far fewer of them established on the ground compared with Southeast Alaska and the Continental U.S., and remeasurements are currently lacking. Sampling intensity has been 1 plot per 12,013 ha (1/5 of the sampling intensity for the continental U.S.), and plots were sampled in 2014 and 2016 to 2020 (n = 898). Therefore, some additional modelling effort was required to extrapolate the existing sample plot data to the whole area. Briefly, the NFI data were used to predict plot-level parameters using non-parametric random forest for regression. Random forest describes the relationship between a dependent variable (e.g., live aboveground biomass carbon) and a set of predictor variables. More detail about this methodology is available in U.S. EPA[12]. Time-series estimates for all of Alaska are presented in Domke et al.[67]. Estimates for the managed interior part of Alaska were inferred from these data combined with data reported in U.S. EPA 2022 and consultation with G. Domke (personal communication).

European boreal forests

In Finland, Norway, and Sweden, forest growing stock volume (nation-wide stem volume) has been reported as a 100-year time series based on empirical observations at intervals of typically 1-8 years[68,69,90]. The vegetation carbon sink was calculated converting stem volume to dry biomass and carbon mass of whole trees, interpolating annual time steps, and thus obtaining the sink in living trees as $C\ stock_{year\ n} - C\ stock_{year\ n\text{-}1}$. This method is referred to as the stock change method. In addition, the flux method was applied drawing on annual observations of increments

(= growth) and decrements (= drain, consisting of harvest losses and natural disturbances and mortality), subtracting the annual decrement from the annual increment .

Regarding forest soils, empirical inventory data on the national C stock are available since the 1990s from Sweden. The Swedish data were extrapolated to Finland and Norway proportional to the forest area of the three nations. Moreover, soil carbon models were examined for defining the input of C in litter and the organic mor layer, and the losses of C in decomposition and leaching. Results for the stocks and stock changes of soils and litter were checked for consistency with the country data reported to UNFCCC[10].

Continental United States and Southeastern Alaska

Forest area estimates for specific years are from the United States (U.S.) Forest Inventory and Analysis (FIA) as reported for all temperate forest lands of the continental U.S. and Alaska[11]. Estimated area of afforestation was from the U.S. EPA[71]. Deforestation area was calculated as the area needed to account for the total area change after estimated gains from afforestation. Estimates of forest C stocks in the U.S. are based on the U.S. Forest Service Forest Inventory and Analysis (FIA) data base, as reported[72]. FIA statistics are compiled from a very large sampling of U.S. forest lands – about 130,000 forested sample plots are inventoried on a rotating annual basis. Statistical estimates of forest area, species, and stand density are converted to ecosystem carbon estimates using standard procedures and following national and international accounting and reporting guidelines. Details of the methodology are available in USDA[73] and USEPA[74], so only a brief overview is presented here.

Forest tree biomass (live and dead) is estimated directly from the inventory measurements using allometric equations. Other C pools (down woody debris, forest floor, understory biomass, and soil C) are estimated using simple empirical models[71], parameterized from measurements at a subset of national inventory plots, and ecosystem studies that related these variables to observed forest characteristics from the inventory.

Estimates of soil C stocks account for a soil depth of one meter, and include the effects of land-use change and forest type shifts, but not increases or decreases on forest land that does not change forest types over the inventory period. Estimates of changes in soil C stocks do not include that portion of the soil C that is transferred into or out of the forest land classification. The carbon in harvested wood (remaining in use and stored in landfills) is estimated using a model that converts removals data to C stocks based on tracking of wood processing and decay rate functions[75]. The uncertainty of the estimated annual change in forest and wood products C is about 10% at the 95% confidence level[71]. These uncertainty estimates are based on a Monte Carlo uncertainty analysis of the mean estimates.

Temperate Europe

The data for Europe were obtained from the country reports prepared by 31 European countries for the State of Europe's Forests 2020[13], Greenhouse Gas Inventory for the UNFCCC[14] and the Global Forest Resources Assessment of 2020[15]. The quality and availability of forest area data for Europe is good. The reported values for forest area are generally based on combined remote sensing and aerial photographs, and confirmed by field surveys from national forest inventories. In addition to reporting forest area, most countries also report annual (gross) rates of afforestation and the natural expansion of forest cover. Afforestation, in the terminology of this study, is the sum of these two rates of forest expansion based on State of Europe's forests[13]. Deforestation was inferred from total land use change from forest to other land use types based on the common reporting format to UNFCCC. Three countries lack values for annual afforestation. Depending on the sign of the net change of forest area in these countries, it is included in the regional totals as either afforestation or deforestation.

The estimates for carbon in living biomass in Europe are based on repeated field surveys from national forest inventories that measure growing stock volume. Growing stock volume is converted to biomass, and biomass to carbon, using national factors developed by country-specific research, with the exception of Greece. Based on national forest inventory uncertainty analyses, we can state that the quality of these data is good to very good. Net annual increment is derived from the repeated inventories and converted to biomass, and biomass to carbon, using national factors developed by country-specific research.

The availability of data on carbon in dead wood is more restricted; approximately half of all European countries lack these data for at least one reporting year. Where data were missing, carbon in dead wood was estimated by applying ratios of dead wood carbon per hectare to forest area. For countries that lacked data for some year(s), these ratios were extrapolated based on data for other years. For countries entirely lacking data, these ratios were adopted from the country with the most similar climate and forest-use history. In these cases, the estimated ratios were constant and based on data from 1990. Due to data deficiencies, the accuracy and precision of the regional estimates of the dead wood C stock are weaker than the corresponding estimates for living biomass.

The availability of data on C stocks in litter and soils is also limited. Of the 31 European countries included in the analysis, 15 reported soil C for the whole period (1990-2020). Austria, Denmark and Germany use data from their respective forest soil inventory, while most other countries use forest area-based extrapolations.

In this study, the C stocks in litter and soils for countries that lacked data were estimated by using area-based litter and soil C ratios. For countries that lacked data for some year(s), these ratios were extrapolated based on data for other years. For countries entirely lacking data, these ratios were adopted from the country with the most similar climate and forest use history. In these cases, the estimated ratios were constant and based on data from 1990. Available estimates were adjusted to a standard depth of one meter if a different depth was used, based on a model of soil C by depth reported in Jobbagy and Jackson[76]. Estimates of the C in HWP were derived using the method described earlier in the general methods section.

China

We estimated forest biomass C stock and its change during the 1990s, 2000s and 2010s for China using biomass expansion factors for each forest type and China's forest inventory data for the periods of 1989-1993, 1994-1998, 1999-2003, 2004-2008, 2009-2013, and 2014-2018[16]. Since 1994, the definition of forest in China's forest inventory has changed from >30% canopy coverage to >20% canopy coverage. We therefore calculated forest area, C density, and C change for 1989-1993 based on the new criterion (20% canopy coverage). Analyzing the 1994-

1998 inventory data that provide both criteria (20% and 30% canopy coverage), we found that there exists a robust linear relationship for the forest area and timber volume between the two criteria at the provincial level (Equations 1 and 2):

$AREA_{0.2} = 1.290\ (AREA_{0.3})^{0.995}$ ($R^2 = 0.996$, n=30) (1)

$TC_{0.2} = 1.147\ (TC_{0.3})^{0.996}$ ($R^2 = 0.995$, n =30) (2)

where $AREA_{0.2}$ and $AREA_{0.3}$ are forest areas (10^4 ha) in a province under the two forest criteria, >20% and >30% canopy coverage, respectively; TC0.2 and TC0.3 are total forest C stocks in province under the two criteria. The provincial forest areas and C stocks with the new criterion in 1989-1993 were calculated based on Equations 1 and 2, followed by derivation of the corresponding forest C densities for the different C pools[17]. We used the methods and results by Zhu et al.[18,19] to estimate carbon stocks in deadwood, litter, and harvested wood product in different inventory periods. Carbon in soil to a depth of one meter was estimated using ratios of soil C to vegetation biomass[18,20].

Japan

We used the national inventory data of forest areas for 19 age classes (1–5 yr to > 90 yr) for major tree species such as sugi cedar and hinoki cypress and natural and afforested conifer and broad-leaved forests[21]. The data is available for the years 1985, 1990, 1995, 2002, 2007, 2012, and 2017; in other years, forest areas were linearly interpolated or extrapolated (after 2017). Areas of afforestation, reforestation, and deforestation were also obtained from the national inventory. Average biomass C stock for each age-class and forest type was estimated using the Forest Ecosystem Biodiversity Survey conducted in 2004–2008 and 2009–2013 by the Japan Forestry Agency (https://www.rinya.maff.go.jp/j/keikaku/tayouseichousa/). From 23,270 records by each survey, valid forest age and aboveground woody volume data were extracted and used for aggregation. The values were converted into total tree C stock by using biomass expansion factor (1.23–1.57), root-shoot ratio (0.25–0.26), wood density (0.314–0.50 t wood m^{-3}), and carbon content (0.48–0.51 t C t^{-1} wood) data. Differences in the biomass expansion factor between young (< 20 yr) and mature (≥ 20 yr) stands were considered. By applying the average C stock to the age-class area data, we obtained total biomass C stock. The ranges of estimation uncertainty were obtained by considering the variance of forest area, expansion factor, root-shoot ratio, wood density, and carbon content. We conducted the estimation 10,000 times using randomly sampled parameters and obtained the average and standard deviation of the total C stock.

Soil and litter C stocks were estimated on the basis of survey data by the Forestry and Forest Products Research Institute[77]: on average, 0.42 ± 0.67 kg C m^{-2} for dead wood, 0.49 ± 0.32 kg C m^{-2} for litter, and 14.29 ± 8.38 kg C m^{-2} for soil (0–1m) organic matter. Temporal change in the soil and litter C stocks was simply estimated using the year-by-year change in forest area. C stock in harvested wood products was estimated by the method by Johnston and Radeloff[78], using data from the national statistics report of wood supply and demand[79].

Australia

Australia has a national greenhouse gas inventory system that reports changes in forest area and carbon stocks since 1990. Area of forest and annual changes in area are derived from a consistent time-series assessment of land cover change based on Landsat remote sensing since 1972. Carbon stocks and stock changes in biomass (above- and below-ground living biomass, dead biomass and litter) and soil are calculated using spatially referenced data integrated into an empirical process-based model based on a mass balance approach.

Data sources included the Australian National Inventory Reports 2016, 2018; State of the Forests Report 2018; National Greenhouse Gas Inventory Quarterly Update June 2020; Australian Greenhouse Emissions Information System. These data were used in combination and cross-checked[22,23,24,25,26,27].

The forest area reported comprises all land with woody vegetation with threshold minima of 2 m height, 20% canopy cover and forest areas of 0.2 ha. Forest land includes areas that potentially could reach these threshold values of the definition of forest land but are temporarily unstocked and expected to revert to forest.

Forest land consists of three categories depending on their land use and land use change.

1. Forest remaining forest land:

Harvested native forests: emissions and removal due to loss of biomass from timber harvesting, salvage logging, regrowth following harvest or fire, decay of harvest slash, prescribed burning, and transfer to harvested wood products.

Pre-1990 plantations: emissions and removals as above.

Other native forests (continuously forested since 1972): growth of trees and change in soil carbon are not included as carbon uptake is presumed to be balanced by carbon losses (however, this assumption likely leads to underestimation of carbon stocks and removals, as shown by Keith et al.[80]. Emissions and removals due to fire management practices are included. Emissions from wildfires are included as long-run average carbon losses after applying the natural disturbance provision.

2. Forest land converted to other uses (deforestation): Carbon stock change includes emissions and removals from direct human-induced removal of forest and replacement with pasture, crops, settlements, or other uses since 1972. Emissions occur due to burning and decay of cleared biomass and changes in soil carbon from current and past activities.

3. Land converted to forest (afforestation): Carbon stock change includes emissions and removals from forest regrowth on previously cleared land, regeneration of forest from natural seed sources, environmental plantings and new plantations.

Change in forest area over the decade is calculated as the sum of gains from afforestation and the losses from deforestation. Net carbon stock change is calculated from the carbon stock data for the areas designated as forest land remaining forest land, forest land converted to other uses and land converted to forests. Carbon stock change is reported separately for the areas of forest land converted to other uses (deforestation) and land converted to forests (afforestation). Carbon stock change per area is calculated for the average area of forest land within the category over the decade, not the area change for each year.

Areas of deforestation are differentiated as:

1. Clearing of primary forest that had not previously been cleared (based on remote sensing monitoring since 1972).
2. Clearing of young secondary forest that had re-grown on previously cleared land.

Carbon stocks modelled in the inventory were calibrated with site data for estimated forest biomass to derive an initial forest biomass layer. In the inventory, this initial biomass is used to calculate carbon stock loss due to first-time clearing events since 1990. Initial biomass was equated with a 'mature' forest without recent disturbance that was assessed since 1970; however, this does not necessarily represent a primary forest (that is, a forest not affected by human disturbance events)[81]. Sites include forests that had previously been grazed, prescribed burnt, selectively logged or clearfelled and regenerated to an age approximating the harvest age. Additionally, minimally disturbed forests in protected areas, which have the oldest age classes and high carbon density, are under-represented in the site data. Hence, the biomass carbon stocks are likely underestimates for areas of primary forest and particularly high carbon-dense forests. Soil carbon is modelled based on spatial data for soil type, clay content, climate and environmental variables. Stock changes due to rates of inputs and decomposition are modelled as the dynamics of three soil carbon fractions based on functions of the interaction of climate, soil and land management practices.

Old growth forest, defined by stand structural characteristics, is estimated to exist on 23% of the area of multiple use forests (15.4 Mha), but is only assessed for a small proportion of the total area of native forest.

<u>New Zealand</u>

The data sources are from the national reports titled "*New Zealand's Greenhouse Gas Inventory 1990–2019*"[28] and New Zealand's national report to *Global Forest Resources Assessment 2020*[15]. These reports provide information of carbon stocks and sinks in forest lands, different forest C pools, forest areas, and harvested wood product over three decades. The data from different resources were cross-checked and used to supplement each other to produce the estimates in this study. For instance, there are detailed data of different C pools (C in above-ground biomass, below-ground biomass, dead wood, litter, and soil) in the FAO report, which were used to calculate carbon sequestration in different components for the 1990s, 2000s, and 2010s to meet the requirements of this study.

Other European Countries, Korea, and Other Countries in Temperate zones

Due to lack of other data sources, the calculations for these countries/regions are exclusively from national reports in "*Global Forest Resources Assessment 2020*"[15] and several publications of FAO Yearbook of Forest Products covering 1990 to 2019 [,82,83,84,85,86,87,88,89,90]. The FAO report[15] provides information of forest areas, carbon stock density (or carbon stock), and stock densities in different carbon pools for decades from 1990 to 2020, which enable calculation of nations' total forest C stocks and stock changes. However, not all countries reported all categories for calculating variables required in this study. For instance, the category of Other European Countries includes Ukraine, Belarus, Georgia, Armenia, Azerbaijan, and Turkey. Among these six countries, Ukraine, Belarus, and Turkey have information of stocks in living biomass, dead wood, litter, and soil; Georgia has information about carbon stocks in living biomass, litter and soil, while Amenia and Azerbaijan only have stock information of living biomass. In the case of Georgia, it could be due to a different classification that includes deadwood in the litter category. Nevertheless, we summed up carbon stocks and stock changes in different carbon pools, which could be underestimated because of missing data in some countries. For harvested wood product (HWP), we used annual reports of harvested roundwood and calculated decadal averages; and converted wood volume to biomass and carbon using coefficients suggested by IPCC[91]. Finally, we used the ratio (see the above method for HWP) to calculate HWP, i.e. about 9.5% of carbon in harvested roundwood product.

India

The agency of Forest Survey of India produces the India State of Forest Report biannually. The reports from 1989 to 2019, which provide forest carbon stocks of surveys (in every two years), were used as data sources for estimating some variables in this study[29]. The data from FAO's Global Forest Resources Assessment[15] were also used for cross-checking and supplementing the information not included in India State of Forest Reports to fulfill the need of this study. India's forest inventory reports have been continuously improved over the years. In the earlier reports, only forest areas were reported. Later, information of wood volumes was added. In more recent reports, which appeared to follow the IPCC standard, carbon stocks in different forest pools were reported. We were able to combine different data sets to derive estimates for this analysis.

Other South Asia countries

This category includes Pakistan, Nepal, Bhutan, Bangladesh, and Sri Lanka. Our estimates here, as for Other European Countries, were based on the country reports to FAO Global Forest Resources Assessment[15] and the FAO Yearbook of Forest Products[82,83,84,85,86,87,88,89,90]. These FAO countries' reports do not always have complete data on carbon stocks. In the national inventories and Nationally Determined Contribution (NDC) reports, some countries often provided larger carbon sink estimates[47]. However, considering that some NDC reports are lacking from these countries and their total carbon stock and sink do not significantly affect our global estimates, for consistency we used the FAO data in order to include all these countries in the list, although likely there are underestimates of carbon stock and carbon sink for this category. The estimation approaches for Other South Asia Countries are the same as used for Other European Countries, Korea, and Other Countries in Temperate zones (see above descriptions).

Intact Forests of Tropical America, Africa, and Asia

Area estimates for Africa, South America and Southeast Asia follow Hubau et al.[31]. We distinguished major forest areas within South America as follows: Andean mature forests, following Duque et al.[92], Western Amazon intact forests, following Phillips and Brienen[93]; remaining Amazon & extra-Amazon non-Andean dry, moist, and wet mature forests, from Hubau et al.[31].

Carbon stock and stock change estimates are based on networks of permanent inventory plots in intact forests across tropical Africa, South America, and Southeast Asia. Methods for permanent plot work and data quality control are detailed elsewhere[31,40,94]. The database[95] consists of tree-by-tree long-term forest demographic datasets from multiple tropical networks that include more than 500 research partners tropics-wide[96]. We assume that the same proportional net change detected in biomass of trees $\geq$10cm diameter occurs in all biomass compartments not monitored directly (shrubs, saplings and lianas, below-ground, necromass, and litter). We do not account for possible changes in soil C stocks or harvested wood C stocks using the plot data (for estimates of these pools, see sections in general methods describing soils and harvested wood products).

For Africa the total sample is 244 plots with a median area of 1 ha, a mean census interval of ≈ 6 years and a mean plot monitoring period of ≈ 12 years. We estimate mean net fluxes over each decadal period using plots censused in that period scaled by intact forest area, following the methods and results of Hubau et al.[31]. For South America the total sample is 440 plots (321 Amazon, 119 Andes), with a median plot area of 1 ha, a mean census interval of ≈ 3 years and a mean monitoring period of ≈ 11 years. We estimate mean net fluxes over each decadal period using plots censused in that period. We followed the methods of Hubau et al.[31], while for 2000-9 and 2010-19 additional regional compilations of permanent inventory data allow us for the first time to account separately for Andean forests[92] and for western Amazon forests[97], with the area of intact Andean forests defined following Duque et al.[92], and the area of Western Amazon following Phillips and Brienen[93].

For tropical Asia the per unit area aboveground live biomass C sink is the area-weighted mean of Southeast Asian sink values, derived from published per unit area carbon sink data (n = 49 plots) for 1990-2015[30,31].

Carbon fluxes in belowground biomass, deadwood and litter were estimated using available data of expansion factors for South America, Africa, and Southeast Asia, respectively, as reported in Hubau et al.[31].

Because there are no available soil C sampling data for estimating soil C stock changes, we searched FAO country reports[15] in tropical and subtropical regions that reported soil C stocks. Only a handful of countries were found including Argentina, Brazil, Chile, Ecuador, and Myanmar. The average soil C stock change rates were calculated and used as area-based soil C stock change rates for 1990-1999, 2000-2009, and 2010-2019 and applied for South America, Africa, and Southeast Asia, being respectively 0.0245, 0.0210, and 0.0355 Mg C ha^{-1} yr^{-1} for three continents. Given the sparsity of data the quality of soil C stock change estimates for those regions is poor and has substantial uncertainty.

All analyses presented here refer to our dataset of tropical wet, moist, and dry forests. These ecozones represent the large majority of intact forest types on each continent (>90%). However, some tropical forest types which cover comparatively small areas lack sufficient on-the-ground monitoring to know their biomass density trajectory (notably: remnant sub-tropical and temperate forests in southern South America, mountain forests, drier forests in Africa, and tropical swamp forests in each continent). For these we assume the same trajectory of biomass change as for the monitored forest types.

The soil carbon stock data for the tropics are incomplete, with only partially available data for 2000 from Africa and South America. To address the data gaps, we first used published data to estimate initial carbon stocks. The soil C stock density for Africa in 2000 was estimated based on the area-weighted soil C stock densities of Africa forests (except mangrove forest)[36]. For Southeast Asia C stocks (both biomass and soil) in 1990, we estimated aboveground biomass density using the mean aboveground C stock density from 71 forest plots across Borneo[30]. We used the weighted belowground biomass densities for the Southeast Asia region[32] to estimate belowground biomass C stock in 1990. For soil carbon, we also used regional weighted densities (soil C to 100 cm depth) from Brown et al.[32]. Finally, we assumed that the weighted soil density included deadwood and litter components, and then partitioned the total to estimate stock densities of deadwood, litter and soils using the ratios of deadwood to living biomass and litter to living biomass, using the average of these ratios from South American and African forests.

With the initial carbon stocks (2000 for Africa and South America, and 1990 for Southeast Asia), we applied the method for calculating C stocks for other years. In estimating these, we considered the effects on C stocks of within-forest C fluxes and the loss of intact forest area.

For forward year calculations:

$$\text{C stock }(t+1) = \text{C stock }(t) - \text{C density }(t)^{*}\ \text{Area}_{lost}\ (\Delta t) + \text{C uptake }(\Delta t)$$

$$\text{C density }(t+1) = \text{C stock }(t+1)/(\ \text{Area }(t) - \text{Area}_{lost}\ (\Delta t)) = \text{C stock }(t+1)/\text{Area }(t+1)$$

For backward year calculations:

$$C\ stock\ (t-1) = C\ stock\ (t) - C\ uptake\ (\Delta t)$$

$$C\ density\ (t-1) = C\ stock\ (t-1)/(Area(t) + Area_{lost}\ (\Delta t)) = C\ Stock\ (t-1)/Area\ (t-1)$$

Here, the equations were applied for each component (biomass, deadwood, litter, and soils).

Overall, we have medium confidence in the long-term biomass sink and trends in most intact tropical forests (South America, Africa and Southeast Asia), where sample sizes are large enough to detect small changes over large-scales[98], but we have lower confidence in sink trends in less well sampled regions and periods (South America since 2012, African dry forests, and Southeast Asia). We have least confidence in the trends in non-biomass components for which sequential monitoring is largely absent.

<u>Mexico</u>

Mexico's forest area estimates and estimates of afforestation and deforestation were taken from the FRA 2020 database[15]. The area of intact tropical forest was assumed to be the same as the area of primary forest as defined by Mexico in FAO 2020, and the remainder of the total forest area was classified as tropical regrowth. The total carbon stock of Mexico's forests was taken from FRA 2020[15], and partitioned to intact and regrowth categories according to the ratio of carbon stocks for these two categories as shown in the 2019 update to the IPCC guidelines, table 4.7[39]. Similarly, the C stock change estimates of biomass were calculated as the ratio of intact to secondary stock-change of biomass based on[33] table S6. The C stock change estimates for dead wood, litter, and soil C were based on the ratio of these individual pools to live biomass that were calculated for South America intact and regrowth tropical forests.

<u>Central America and Caribbean</u>

Forest area estimates and estimates of afforestation and deforestation for Central American and Caribbean countries were taken from the FRA 2020 database[15]. The area of intact tropical forest was taken from Potapov et al.[38], and the remainder of the total forest area was classified as tropical regrowth. The total carbon stock of forests in Central American and Caribbean countries was taken from FRA 2020. A few countries did not report C stocks, so estimates from those countries that did report were extrapolated to those that did not report. Total C stock was partitioned to intact and regrowth categories according to the ratio of carbon stocks for these two categories as shown in the 2019 update to the IPCC guidelines, table 4.7[39]. The C stock change estimates of each C pool were based on removal factors from Cook-Patton et al.[33], representing regrowth forests of ages 0-30 years for tropical and subtropical South America. Additional details of the Cook-Patton et al.[33] approach are reported in the following section on tropical regrowth forests.

Tropical Regrowth Forests

The areas of tropical regrowth forests for 1990, 2000, 2010, and 2020 for each region were based on data reported by Hubau *et al.*[31], Houghton *et al*.[99,100], and Forest Resources Assessment 2020[15]. We adjusted the area estimates from different sources to be consistent with total tropical forest areas reported by Forest Resources Assessment[15]. The regrowth forest areas of three major tropical regions (Southeast Asia, Africa, and South America) were based on FAO total tropical forest areas[16] minus intact forest areas reported by Hubau *et al.*[31]

To estimate carbon stocks for different regions, we used the forest carbon densities (Mg C ha^{-1}) data of the Global Forest Resource Assessment[101], and calculated C stock change per area (Mg C ha^{-1} yr^{-1}) of tropical regrowth forests (Southeast Asia, Africa, and South America) for 1990s and 2000s to derive C densities of 1990 (including densities of living biomass, deadwood, litter, and soils) for these three regions:

$$\text{C density (Mg C ha}^{-1})_{1990} = \text{C density (Mg C ha}^{-1})_{2005} - \text{C stock change (Mg C ha}^{-1}\text{ yr}^{-1})_{2000s} * 5 - \text{C stock change (Mg C ha}^{-1}\text{ yr}^{-1})_{1990s} * 10$$

After setup initial C stock density in 1990, we calculated C stocks for other years using regrowth forest areas:

$$\text{C stock (Mg C)}_{1990} = \text{C density (Mg C ha}^{-1})_{1990} * \text{Regrowth Area (ha} * 10^{6})_{1990}$$

We used the equation for calculating C stocks in the following decades:

C stock (Tg C) $_{T+1}$ = C stock (Tg C)$_T$ + C uptake (Tg C yr^{-1}) $_{\Delta T}$*10 years

Here t = represents a decade, so t+1 for 2000, 2010, and 2020, while Δt represents the decade between T+1 and T. Also, C stocks usually use the unit of PgC, which equals MgC*10^9 or TgC *10^3. The C stocks for a few other countries were estimated directly using FAO data[15].

To estimate stock changes for tropical regrowth forests, we used the stock change estimates reported by Cook-Patton et al.[33] for live biomass, representing regrowth forests of ages 0-30 years for tropical and subtropical regions, also accounting for the area of dry, moist, and wet forest ecozones within each region. We chose this source because the estimates focused on the young ages typical of tropical regrowth yet were assumed linear and so are relevant for slightly older ages of regrowth forests, and also reflected the historical origins of them as represented by the type of disturbance that created the regrowth. The estimates are based on a large database derived from literature estimates of forest regrowth. Together with the C stock data of country reports in tropical regions[15], as well as data extrapolations, we estimated stock changes for each period for dead wood, litter, and soils, using the ratios of these values to live biomass as previously reported[35].

To validate our estimates of stock changes, we compared the growth estimates for tropical regrowth forests with other estimates from the literature[102,103] and summarized (Table S7)[104,105]. Our estimates are comparable to those recommended by IPCC and to other literature sources for tropical Asia and America, but lower than other estimates for Africa, primarily because of the larger proportion of dry forest areas in Africa that have enhanced growth due to improved water use efficacy with elevated atmospheric CO_2[106,107]. Because of the lack of statistical surveys and permanent sample plots, the uncertainty of estimated regrowth values for secondary tropical forests is large, estimated by literature[33] and expert opinion to be from ±50% to ±75% . This value for the 95% confidence level (see the following section for uncertainty estimation) was chosen for two reasons: (i) the uncertainties were greater than those estimated for tropical intact forests, which were derived directly from measurement data; and (ii) the uncertainties are consistent with the widely reported uncertainty (~0.7 Pg C yr^{-1}) in tropical land-use emissions (that variable includes regrowth offset).

Gross emissions from tropical deforestation

Gross emissions from tropical deforestation were obtained from Houghton and Castanho[104]. That study used a bookkeeping model to calculate sources and sinks of carbon as a result of land use, land-use change, and forestry (LULUCF). Gross emissions from deforestation included losses of carbon from burning and decay of biomass accompanying deforestation, as well as losses of organic soil carbon resulting from cultivation of soil following deforestation for croplands. Rates of deforestation were determined by the net rates of forest conversion to croplands, pastures, or other lands[108]. Gross emissions from deforestation are nearly identical to net emissions from deforestation because, by definition, deforestation is a loss of forests. It does not include forest recovery. The estimates of deforestation gross emissions in Southeast Asia also included peat swamp forests in western part of insular regions, which lost 2.0-2.5 Pg C per decade[109]. The C loss did not only come from the biomass removed but also from the oxidation of the drained peatlands[110].

The gross emissions from tropical deforestation were lower in this analysis than reported in Pan et al.[35] because the earlier study included the gross emissions from repeated re-clearing of forest fallows in the shifting cultivation cycle. In this study we recognized that the re-clearing and re-growth of fallows are not deforestation and reforestation. Rather they are emissions from a non-forest land use (i.e., shifting cultivation).

Supplementary results for forest area and carbon pools

Global forest areas

Detailed information about the area of global forests, by country/biome and year, including estimates of afforestation and deforestation, is shown in Extended Data Table 1. The largest area of forest land is in the tropics, followed by boreal and then temperate forests. Globally, the area of forest land declined by 5% between 1990 and 2020, due to the loss of tropical intact forest, which exceeded gains in the area of temperate forests and tropical regrowth forests. Boreal forest areas were relatively stable through three decades.

In Extended Data Table 1, areas of afforestation and deforestation were either derived from country inventory data or from country reports of FAO[15]. Changes caused by afforestation and deforestation do not always match well with total forest area changes in the table and appear to underestimate afforestation (or overestimate deforestation) in temperate regions, overestimate afforestation in boreal regions, and underestimate deforestation in the tropics. Nevertheless, they provide some general information about dynamics in these forest areas.

Afforestation was greatest in temperate forests especially in China, which accounted for more than 80% of all afforested areas in temperate forests for the 1990s and 2000s (> 40 Mha) although by the 2010s the newly afforested area was reduced to only ~40% of that of the 2000s decade, likely due to limited lands available for tree planting (Extended Data Table 1). Temperate Europe, Australia, and the U.S also had considerable afforestation areas, together reporting a consistent ~8 Mha through each decade. While afforestation in temperate Europe gradually decreased from the 1990s to 2010s (4.5 to 2.5 Mha), Australia had steadily increasing afforested areas (2.2 to 4.4 Mha) and by the 2010s afforested lands were slightly greater than the total deforested area (Extended Data Table 1). Afforested areas in the U.S. of ~ 1.4 Mha each decade were rather small compared to the country's vast forest area. Russia also showed some gains in afforested areas in both Asian and European Russia (together on average about 6 Mha per decade). However, these new forests are natural encroachments of trees and shrubs in abandoned agricultural lands rather than deliberate afforestation by human activities and their area will be subject to substantial regrowth dynamics.

Deforestation, by definition, is transformation of forests to other land-uses, which was significantly greater in the tropics, particularly in converting intact forests to agricultural lands or to economic tree plantations such as oil palm. However, deforestation was also fairly extensive in temperate zones, particularly in the 1990s, and decreased by about 73% since then (from 51 to 14 Mha). Deforested lands (~40 M ha) in China in the 1990s were almost equal to afforested lands but the deforestation rate later reduced to 14% owing to strict policies protecting forests. Australia had considerable deforestation for the 1990s and 2000s (~ 6.5 Mha), but this was reduced by relevant policies in the 2010s (to 4.2 Mha). Decadal deforested areas in the U.S. were about the same as afforested areas until 2010, but then deforestation increased to exceed afforestation in 2010s. Deforestation in temperate Europe was minimal but also had an increasing trend over three decades. Nonetheless, while different temperate countries/regions had some differences in afforestation and deforestation dynamics, in general, deforestation in temperate forests overall was always less than afforestation to result in expansion of forested lands for this biome.

Carbon stocks (pools) and fluxes (sink or source)

Compared with living biomass, estimates of these variables usually have higher uncertainty in both stocks and fluxes, because data are often insufficient due to lower sampling intensities and measurements. However, these C stocks and fluxes provide critical information about carbon dynamics and structures of forest ecosystems that enable better understanding of the impacts of environmental drivers and disturbances.

Deadwood, litter, soils, and total necromass (non-living organic matter)

Globally, the C stock of deadwood is estimated to be a small but significant component of the forest C stock (on average ~9% of total over three decades, Extended Data Table 2), while the estimated C sink in deadwood is about 8% of the total sink and was stable through the decades although there were regional changes in deadwood sinks (Extended Data Table 3). The C stock of litter averaged ~4% of the total C stock mostly because of small quantities of litter in tropical forests, while the C sink in litter accounted for only about 2% of the total sink on average through the decades.

There was a significant increase of the C sink in deadwood in boreal forests (+53%), representing an increase from 14% to 33% of the total C sink from the 1990s to the 2010s along with a 36% reduction in the total C sink (Extended Data Table 3), making a large but possibly transient contribution to the total C sink in the high latitudinal belt, which reflects intensified impacts of disturbance (wildfires and insect outbreaks) that mainly occurred in Russian Siberian and Far Eastern forests. Meanwhile, the C sink in litter in boreal forests decreased by 40% from the 1990s to 2010s, suggesting that this result is based on the effects of increased wildfires on consumption of litter, and the effect of warming on accelerating decomposition in the region.

In temperate forests, particularly European temperate, a substantial part of which is intensively managed, the deadwood C sink was ~9% of the total C sink in 1990s and decreased to ~6% in 2010s, possibly due to episodic disturbances followed by management practices for removing or salvaging dead trees after disturbances including storms, outbreaks of invasive insects, fires, and droughts. On the other hand, the sink in litter increased by 55% with high variability among countries, reflecting both increased living biomass and accelerated carbon cycling[111].

Tropical forests had the largest C sink in deadwood among biomes, which was ~6% of the total sink, and ≈ 9% and ≈3% of the sink in intact and regrowth forests respectively. Given the difficulty in measuring C fluxes in deadwood in tropical regions, the estimates relied on constant C allocation ratios that may not reflect higher tree mortality associated with drought stress in 2000s and 2010s[112,31]. The deadwood sink decreased by 41 Tg C yr^{-1} in the 2010s compared to the 1990s in intact forests, and increased by 11 Tg C yr^{-1} in the regrowth forests, mostly related to forest area changes (decreasing in intact forests, increasing for regrowth forests). The sink in tropical forest litter, however, was small because of fast decomposition and nutrient recycling processes. Therefore, the relatively stable global deadwood sinks overall, were the net result of substantially enlarged deadwood C sinks in boreal forests due to intensified disturbances, decreased sinks in tropical intact forests associated with the lost area, and decreased sinks in temperate forests from forest management for salvaging deadwood.

Besides living biomass stock, soil is another large C pool, and one which is sensitive to thermal differences across the world's forests. On average, the soil C stock is equivalent to about 325% of living biomass in boreal forests, 155% in temperate forests, and only 60% in tropical forests. However, estimates of soil C stock are highly uncertain because of lack of monitoring data with considerably fewer soil C samples compared to living biomass. Regionally there are data inconsistencies due to various soil depths associated with measured data. Although most of the data reported in this study represent soil depths of 100 cm, relatively few measurements were done to that depth and so estimates rely on measurements in shallower soils and model projections. Nevertheless, there were trends of decreasing fractions of soil C in the total C stock but increasing fractions of living biomass C in all forest biomes over time. These shifts might imply some consequences of changing growth conditions, such as an increasing CO_2 fertilization effect[107] or accelerated soil decomposition with increasing temperatures[113].

Harvested wood products (HWP)

Globally, the C sink in HWP was stable from 1990s to 2000s, and then increased by 9% in the 2010s. HWP decreased by 17% in boreal forests, as Canada reduced harvest, while Russia reduced ~13% although the latter does not reflect the reality of increased logging both legally and illegally. There were large increases in HWP in temperate and tropical forests, i.e., 17% and 13%, respectively.

Half of the global harvest of wood is non-commercial fuelwood mostly in developing countries, but not exclusively. For instance, in Europe, the non-commercial household fuelwood is about 20% of total European harvest. Bioenergy commercialization is leading to some increases in harvest, but this varies regionally depending upon management with harvesting predominantly for bioenergy or with use of low-quality residues and side streams from industrial timber harvests. Increasing and sustainable use of harvested wood in future bioeconomies is essential to maintain high rates of C removed by managed forest ecosystems. Despite increasing recycling rates of wood residues[114] and efforts to divert organic matter from landfills at the end of product life, HWP are often directed to solid waste disposal sites where a fraction of C is stored for long periods of time. However, even if only 4% of the HWP C directed to landfills is lost to the atmosphere as methane which has a higher global warming potential (GWP of 29 for 100 years)[115] than CO_2, any potential climate benefits of wood storage in landfills have been negated.

Additional results for selected regions and countries

Unmanaged forests of Northern Canada and Alaska Interior

Large areas of unmanaged forests in the Northern Hemisphere lack sufficient ground data for reporting C stocks and changes in C stocks in a way that is consistent with the other estimates. Estimates reported for boreal forests exclude ~121.5 Mha of forests in northern Canada and 8.7 Mha in Alaska Interior (Table S6). These areas are typically remote and not directly affected in a significant way by human activities including fire suppression. Thus, changes in C stocks of these areas are dominated by natural disturbance cycles and changing climate. Estimates made by upscaling data from flux towers or remote-sensing based estimates indicate either a small positive or small negative net flux from these lands[116,117].

Based on the result of managed forests in Alaska Interior, unmanaged forests of Alaska Interior (about one-third the area of managed forests) could provide at most only a small sink for now and so is expected to be relatively insignificant in the context of the boreal biome. However, as we have seen in the managed forests of Alaska Interior (Extended Data Table 3), this sink could quickly turn to a source with increasing carbon releases from deadwood, litter and soils under fires and warming as climate change continues its course, and as was observed in the 2023 wildfire season. Canadian unmanaged forests cover large areas, equal to about half of the area of Canada's managed forests. As Canadian managed forests were increasing C sources over the decades though relatively small (from 0 up to ~50 Tg C yr^{-1}), we may conjecture that Canadian unmanaged forests could be an even smaller C source of around 10 Tg C yr^{-1} unless warming is triggering more C losses from C rich unmanaged forest soils.

<u>Russia</u>

Russia accounted for about 25% of the area of unmanaged forests until 2021 (~205 M ha). According to the governmental order by Ministry of Ecology and Natural Resources of the Russian Federation, all Russian forests should be considered managed, although in the recent Russian Federation 2022 National Inventory Report (NIR) unmanaged forests were categorized[118]. The C sink in Russian forests is assessed for all tree cover areas corresponding the FAO definition of forest (Extended Data Table 1), which and was high during the decade of 1990-1999 and slightly smaller during 2000-2009, and decreased considerably for 2010-2019 (Extended Data Table 3).

Asian Russia, with vast forest lands and a lower average C sequestration rate compared with European Russia, had the largest boreal sink which was more than two times the sink in European Russia in 1990s and 2000s and slightly decreased in the 2000s (-3%). However, the decade of 2010s demonstrated a substantial decline in C sink in Asian Russia forests (-40%), but only a small decrease in European Russia forests (-6%). This is explained by several factors: the increasing variability of climate and drought in vast regions which provokes unprecedented series of natural disturbances that took place during this period. Areas of including forest wildfires, the area of which increased on average in the Asian part by about 3 times in 2001-2019[119], and the share of stand-replacing fire severity of tree mortality of damaged forests exceeded 50% of the total burnt area that resulted in net loss of 50.2 M ha of forests in Russia in 2001-2019[120]; mass outbreaks of harmful pests shifted toward the north at 200-300 km during the last 50 years; and a significant increase in logging was also observed after mid-2000s.

In contrast, there was an increase in the C sink (+8%) in European Russia (Extended Data Table 3) in 2000-2009 that is attributed to several factors: increased areas of forests after agricultural abandonment, reduced harvesting by half, relatively low level of natural disturbances, and changes of forest age structure and tree species composition to more productive stages, particularly for the deciduous forests in European Russia[56,121].

Afforestation includes two processes[91]. Intensive planting of protective forests on non-forest (basically agricultural) land during the first half of 1990-1999 was a heritage of policies of the Soviet Union. During that time, 0.5 million ha of shelterbelts and other protective forest components of landscapes were planted. Currently, according to fragmented statistic information, such areas are negligible, about 15 000 ha yr^{-1}. More recently, natural afforestation of abandoned agricultural land has had a positive impact on the forest sink, but regenerated forests are relatively low productivity, and suffer from lack of management, unstable dynamics due to recultivation activities and insufficient legislation[122,123].

Overall, the estimated C sink of Russian forests in this study is within limits of the results of most recent peer-reviewed publications on the topic and support the recognized trends[124,125], particularly those received by different methods – by inverse modelling[126], remote sensing[127] (for forests of Asian Russia), and data-assimilation systems[128]. DGVMs of previous generations underestimated the carbon sink, probably due to overestimation of heterotrophic respiration of cold territories[129]. Nevertheless, the diversity of the reported results remains high.

Tropical forests

We separated tropical intact forests and tropical regrowth forests in our analysis because of their different natures and histories, but we also grouped them together in order to convey broader perspectives about forest C dynamics in tropical regions. Even though regrowth forests mostly grow on lands that were once occupied by intact forests, tropical forests as a whole (i.e., intact plus regrowth) still declined by 13% in total area (-273 Mha) over the three decades (Extended Data Table 1).

As we noted above, tropical intact forests had significantly reduced land areas and C sinks over the 30 years due to deforestation and other causes, increasing increased drought, whereas tropical regrowth forests had expanded land areas and enlarged C sinks because trees grew back on abandoned non-forest or degraded lands, and their younger vegetation stages had faster tree growth and higher stand-level C gains than intact forests. As a result, rapid carbon gains in regrowth forests offset the diminished C sink in tropical intact forests, meaning that together the total C sink in tropical forests was remarkably constant at 2.56, 2.49, and 2.52 Pg C yr^{-1} over the three decades (Table 1). Note that these estimates do not include emissions from deforestation.

It is of course important to stress that while the younger regrowth forests have greater per-hectare capacity to remove CO_2 than intact forests, this does not mean that replacing intact forests with regrowth forests would have net carbon balance benefit. On the contrary, mature tropical forests contain very high densities of accumulated carbon (stocks), so C losses per unit area of deforested mature forests are approximately two orders of magnitude greater than the annual C sink of any regrowth forests that might replace them.

When tropical forests are removed, about 45% of C stocks in the deforested lands were initially emitted due to land clearing or slash-and-burn agriculture, whereas another 36% of C stocks, primarily in the soil and slash, were left in the lands that changed to other land-use types. Some of this residual C stock would be continuously emitted with shifting cultivations, clearing of regrowth, and additional harvesting. In addition, some C stocks from deforestation were used for wood products, although ~90% of C in harvested timbers was lost in wood processing or used for short-lived materials such as fuelwood and paper products, which accounted for 17% of C stocks in deforested lands with delayed C emissions over 1-35 years. Only ~2% of the C stock in the deforested lands was preserved as HWP such as construction materials, representing a small sink (Extended Data Fig.1).

We note that while individual Amazon droughts in 2005 and 2010 drove short-term reversals of the Amazon biomass sink[41,130], averaging here over longer time-scales shows that the mature forests still acted as long-term, multi-decadal net biomass carbon sinks. A long-term decline in the sink intensity has been attributed to droughts and increasing temperature[31,131].

<u>European boreal forests</u>

In boreal forests of Europe, harvesting has been the predominant type of decrement especially since the early 20th century, when fire management was implemented to control wildfires. For the period 2010-2017 the carbon sink in living trees was estimated at 6.9, 5.9, and 13.2 $MtCyr^{-1}$ in Finland, Norway, and Sweden, respectively[10]. These estimates were lower for Finland but higher for Norway and Sweden compared to an earlier reference period 1990-1999: 8.5, 4.6, and 8.4 $MtCyr^{-1}$, respectively. Results based on the stock method vs. the flux method did not indicate bias nor large inconsistencies noting the multiple steps of conversion and interpolation[10]. From 2017 to 2020, a decrease of the forest carbon sink was recorded especially in Finland and Sweden[132,133].

In general, an upturn of the carbon sink in forest vegetation occurs if forest growth improves and/or biomass decrements are mitigated. A rising trend of forest growth has maintained the carbon sink in the living trees in European boreal forests over long-time horizon since 1970[68,69,70]. In Finland in 1971–2020 for example, the annual forest growth increased by more than 70%. The decrements have concurrently did not decrease. Had the forest growth not accelerated, a carbon sink in living trees would not have existed.

The trend of forest growth saturated and slightly dropped in Finland and Sweden after 2017, now subject to intensive research[132,133,134]. Changes of roundwood imports also played a role. Roundwood imports from Russia to Finland peaked in 2007 at 18 million cubic meters annually, then decreased and ceased completely after the Ukrainian crisis in 2022; a change implying that harvest burden shifted from Russian boreal to European boreal forests. 18 million m^3

corresponds to whole wood carbon of 6.5-7.0 $MtCyr^{-1}$. Also, an upturn of international markets in 2017-2020 for lumber, pulp, and board attracted record harvests of domestic roundwood in Finland and Sweden. A new study based on 272 024 sample trees reported a reduction since 2014 in Scots pine growth in Finland for unknown reasons[132]. A similar recession of forest growth has been recorded in Sweden[133]. In Sweden, the pan-European drought of 2018 reduced forest growth[134].

In summary for the European boreal forests, the carbon sink of living trees emerged and extended in the 1960´s and 1970´s, then slightly increased or remained stable until about 2017, when a combination of changing imports, harvests and growth lowered (in extreme years 2018 and 2019 nearly halved) the annual carbon sink at least temporarily. The carbon sink in the organic soil layers of litter, mor and peat is estimated to be small, and is most uncertain on drained peatland forests[135] .

Comparison with FAO Forest Resources Assessment 2020

For forest area, our results are generally consistent with those of the FAO Forest Resources Assessment 2020[15]. Where differences exist they are mostly relatively small and consistent with expectations. Thus, across the three decades of our analysis, the global forest area in our study's results is about 6% lower than FRA 2020, largely because we excluded some areas lacking data (Table S6). There were also some differences for two large countries based on the definition of forest. For China, our area estimate was based on 20% canopy coverage which is the new standard there, compared with the more common 10% coverage used in FAO reports (see details of China methods). Our study estimated China's forest area to be 174 M ha compared with 220 M ha reported to FAO. For Russia, our analysis was based on forest area estimates developed specifically for this study since the data reported to FAO were based on old data extrapolated to more recent periods (see details of Russia methods). Our study estimated Russia's forest area to be 834 M ha, compared with the 815 M ha reported to FAO.

A notable difference of our approach compared to that of FRA 2020 is that we partitioned total tropical forest area into "intact" and "regrowth" forests, whereas FRA 2020 partitioned the same area into "primary" and "secondary" forests. While this nomenclature is similar its application is not identical. We also used removal factors based on permanent sampling plots to estimate stocks and stock-changes, whereas FRA 2020 relied on country reports to estimate variables by country and not sub-categories of forests.

Our results for the total global forest carbon stock in 2020 are higher than reported by FAO. We estimated total C to be 870 Pg C, compared with 662 Pg C estimated by FAO. Biomass C stock was 372 Pg C in our study, compared with 295 PgC estimated by FAO. The estimated stock of C in dead wood was similar at about 70 Pg C in each study.

There are significant differences in the forest land sink (not including emissions from land-use change) in our analysis compared to FRA 2020[15]. Our analysis shows an average forest C sink over the three decades of -13.1 Pg CO_2 with an increasing trend, whereas the sink based on reports to FAO was much smaller on average, -3.3 Pg CO_2 with a decreasing trend as reported by Tubiello et al. (2021)[45]. One difference between approaches is that we included changes in harvested wood products in use and in landfills, whereas FRA 2020 did not include this with the ecosystem C pools. Another is that FAO often assumes that forest remaining forests have a neutral C balance, which is why FAO provides a much smaller carbon sink than the national inventories analyzed by Grassi et al.[46,47] who pointed out this critical issue.

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Table S1a. Summary of methods and main sources of data for estimating area, carbon stocks and carbon stock changes, country/region.

Country /Region	Forest area and changes in forest area	Carbon stocks and carbon stock change (fluxes)	References
Russia	For 1990 – data of the State Forest Account corrected for the bias of forest inventory methods used in Russia in 1960-1990; for 2000-2019 – complementary use of remote sensing and ground data	The system of multi-dimensional regression equations for assessment biomass extension factors by components of live and dead biomass applied to the hybrid data base on Russian forests	Shvidenko et al.[1,2] Schepaschenko et al.[3] Shvidenko et al.[4]
Canada	Deforestation monitoring program in managed and unmanaged forests and reporting of afforested areas.	Derived from Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) for managed forests only.	Leckie et al.[5] Stinson et al.[6] Kurz et al.[7] ECCC[8]
Boreal Europe	**Finland**: LUKE Statistics database (luke.fi); **Norway**: Statistisk Sentral Byrå (SSB) (2020); Statistics Norway; Agriculture, Forestry, Hunting and Fishing; The National Forest Inventory; **Sweden**: The Swedish Forest Agency (SFA) (2020); The Statistical Database.	**Finland**: LUKE Statistics database (luke.fi); **Norway**: Statistisk Sentral Byrå (SSB) (2020); Statistics Norway; Agriculture, Forestry, Hunting and Fishing; The National Forest Inventory; **Sweden**: The Swedish Forest Agency (SFA) (2020); The Statistical Database.	Tomppo et al.[9] Kauppi et al.[10]
Continental US & Alaska	The US forest Inventory data combined with National Resources Inventory (all lands) data	Forest inventory data converted to carbon with biomass equations and ecosystem carbon models	Oswalt et al.[11] U.S. EPA[12]
Temperate Europe	State of Europe's Forests (2020). Common Reporting Format per country for the UNFCCC.	Common Reporting Format per country for the UNFCCC. Global Forest Resource Assessments from the FAO	Forest Europe[13] UNFCCC[14] FAO[15]
Other European countries	FAO forest inventory data from regional reports of Global Forest Resources Assessment 2020 (summed from countries' data)	FAO forest carbon stocks (of different C pools) from periodic inventories were used to estimate fluxes of carbon stock changes (summed from countries' data).	FAO[15]
China	Nation's forest inventory data	Biomass expansion factors applied to convert volume estimates from inventory data	Yang et al.[16]; Guo et al.[17]; Zhu et al.[18,19]; Tang et al.[20]
Japan	Inventory-based data of Japan Forestry Agency for 1985, 1990, 1995, 2002, 2007, 2012, and 2017	Age-stock relationship was derived from data of the 1st to 3rd forest ecosystem diversity surveys. Area of each age class derived from the Japan Forestry Agency was used to estimate country-level stock change.	Japan Forestry Agency[21]
Korea	FAO forest inventory data from regional reports of Global Forest Resources Assessment 2020	Forest carbon stocks from periodic inventories were used to estimate fluxes of carbon stock changes	FAO[15]

Australia	Forest area and annual changes in area derived from Landsat for the national GHG inventory. All land with woody vegetation > 2m height, 20% canopy cover, >0.2 ha, including temporarily unstocked	National GHG Inventory including harvested native forests, pre-1990 plantations, other native forests (but the latter does not include changes in carbon stocks due to tree growth or soil carbon), deforestation, and afforestation.	Australian Government[22,23,24.25,26,27]
New Zealand	Nation's forest inventory data and New Zealand's Greenhouse Gas Inventory	Forest carbon stocks from periodic inventories were used to estimate fluxes of carbon stock changes.	Ministry for Environment[28] FAO[15]
Other temperate countries	FAO forest inventory data from regional reports of Global Forest Resources Assessment 2020 (summed from countries' data)	FAO forest carbon stocks (of different C pools) from periodic inventories were used to estimate fluxes of carbon stock changes (summed from countries' data).	FAO[15]
India	The State of Forest Reports of India, 1989 to 2019	Forest carbon stocks from periodic inventories were used to estimate fluxes of carbon stock changes	The State of Forest Report of India[29] FAO[15]
Other South Asian countries	FAO forest inventory data from regional reports of Global Forest Resources Assessment 2020 (summed from countries' data	FAO forest carbon stocks (of different C pools) from periodic inventories were used to estimate fluxes of carbon stock changes (summed from countries' data).	FAO[15]
Southeast Asia	The intact forest area was derived from regional studies; the regrowth forest area was the difference between FAO total forest area and the intact forest area	Intact forests: Permanent plots in Borneo and data from Brown et al (82) for estimating C stock densities and changes. Regrowth forests: stock change estimates from global database for biomass, and ratios of other components to biomass from Pan et al.[35].	Qie et al.[30] Hubau et al.[31] Brown et al.[32] Cook-Patton et al.[33] FAO[34] Pan et al.[35]
Africa	The intact forest area was derived from regional studies; the regrowth forest area was the difference between FAO total forest area and the intact forest area	Intact forests: permanent plot network for C density and change. Regrowth forests: stock change estimates from global database for biomass, and ratios of other components to biomass from Pan et al.[35].	Hubau et al.[31] Henry et al.[36] Cook-Patton et al.[33] FAO[34] Pan et al.[35]
Mexico	FAO Forest Resources Assessment	C stock from FRA 2020. C stock change from literature and values from South America.	FAO[15] Harris et al.[37]
Central America and Caribbean	FAO Forest Resources Assessment; intact area from global map	C stock from FRA 2020 and IPCC guidelines. C stock change from literature and values from South America.	FAO[15] Potapov et al.[38] IPCC[39] Harris et al.[37]
South America	The intact forest area was derived from regional studies; the regrowth forest area was the difference between FAO total forest area and the intact forest area	Intact forests: permanent plot network for C density and change. Regrowth forests: stock change estimates from global database for biomass, and ratios of other components to biomass from Pan et al.[35]	Phillips et al.[40,41] Cook-Patton et al.[33] FAO[34] Pan et al.[35]

Table S1b. Subsidiary information of Table S1a for data providers and sources

Country/region	Providers and data sources for estimates, and uncertainty estimation methods
Russia	**Experts for this study**: corrected data of the State Forest Account, combination of remote sensing and ground data, the system of multi-dimensional regression equations, and biomass extension factors by components of live and dead biomass applied to the hybrid data base on Russian forests. Uncertainty estimated using empirical methods for inventory data plus expert opinion for corrections and modeling.
Canada (managed part)	**Expert for this study**: Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS). Uncertainty estimated using Monte Carlo method.
Alaska (managed Interior part)	**Expert for this study**: The US forest Inventory data combined with National Resources Inventory (all lands) data, biomass equations and ecosystem carbon models. Uncertainty based on quantitative methods for sampling errors, and Monte Carlo methods to propagate uncertainties including modeling uncertainty.
Europe (boreal)	**Expert for this study**: Statistic databases of Finland, Norway and Sweden. Uncertainty based on quantitative methods for sampling errors from forest inventories, supplemented with expert opinion for extrapolated estimates.
United States	**Expert for this study**: The US forest Inventory data combined with National Resources Inventory (all lands) data, biomass equations and ecosystem carbon models. Uncertainty based on quantitative methods for sampling errors from forest inventories, and Monte Carlo methods to propagate uncertainties including modeling uncertainty.
Europe (temperate)	**Experts for this study**: State of Europe's Forests (2020), Common Reporting Format per country for the UNFCCC, and FRA 2020. Uncertainty based on quantitative methods for sampling errors from forest inventories, supplemented with expert opinion for extrapolated estimates.
Other European countries	FRA 2020 country reports. The uncertainty was estimated using the expert opinion by assigning 25% uncertainty to living biomass, deadwood, litter, HWP and 50% uncertainty to soil.
China	**Expert for this study**: Nation's forest inventory data, Biomass expansion factors applied to convert volume estimates from inventory data. Uncertainty based on the ranges of the inventory data.
Japan	**Experts for this study**: Inventory-based data of Japan Forestry Agency, Age-stock relationships derived from data of forest ecosystem diversity surveys. Uncertainty in wood C stock was evaluated using Monte Carlo method in which estimation parameters were randomly sampled from standard distributions with observation-based mean and standard deviation. Uncertainty in soil C stock was estimated from the observed range of soil survey data.
Korea	FRA 2020 country reports. Uncertainty based on the expert opinion by assigning 25% uncertainty to living biomass, deadwood, litter, 15% to HWP and 50% uncertainty to soil.
Australia	**Expert for this study**: National GHG Inventory including harvested native forests, deforestation and afforestation, other native forests. Uncertainty based on quantitative methods for sampling errors from forest inventories, and Monte Carlo methods to propagate uncertainties including modeling uncertainty.
New Zealand	**Expert for this study:** Nation's forest inventory data and New Zealand's GHG Inventory. Uncertainty based on the expert opinion by assigning 35% uncertainty to living biomass,15% to HWP and 50% uncertainty to the C components of deadwood, litter and soil.
Other temperate countries	FRA 2020 country reports. Uncertainty based on the expert opinion by assigning 25% uncertainty to living biomass, deadwood, litter, HWP and 50% uncertainty to soils.

India	**Expert for this study:** The State of Forest Reports of India, and FRA 2020. Uncertainty based on the range of original survey data.
Other South Asia countries	FRA 2020 country reports. Uncertainty based on the expert opinion by assigning 35% uncertainty to living biomass, 25% to HWP and 50% uncertainty to the C components of deadwood, litter and soil.
Southeast Asia	**Experts for this study:** Intact forests– data from permanent plots in Borneo and literature for estimating C stock densities and changes for intact forest. Regrowth forests– global database for biomass[33], and ratios of other C components to biomass from Pan et al.[35] Uncertainty estimated from calculations at groups of permanent plots supplemented with expert opinion for modeled variables.
Africa	**Experts for this study:** Intact forests– long-term measurement data from permanent plot network for C density and change. Regrowth forests– global database for biomass[33], and ratios of other C components to biomass from Pan et al.[35] Uncertainty estimated from calculations at groups of permanent plots supplemented with expert opinion for modeled variables.
Mexico	FRA 2020 country report. Uncertainty estimated from calculations at groups of permanent plots supplemented with expert opinion for modeled variables.
Central America and Caribbean	FRA 2020 country report, global forest map, literature and values of South America for C stock change. Uncertainty estimated from calculations at groups of permanent plots supplemented with expert opinion for modeled variables.
South America	**Experts for this study:** Intact forests– long-term measurement data from permanent plot network for C density and change. Regrowth forests– global database for biomass[33], and ratios of other C components to biomass from Pan et al.[35] Uncertainty estimated from calculations at groups of permanent plots supplemented with expert opinion for modeled variables.

Table S1c. Lists of the data sources used to compile estimates.

Note: Some sources include original data from sampling, and some do not include original data but rather include aggregated data, depending on policies for data sharing that vary from country to country. Because the links to data shown in the table may change over time, the authors cannot guarantee that these links will still be working. In this case, we recommend contacting the responsible authors directly to get updated information about sources of data.
Canada: Canada's 2023 National GHG Inventory Report (NIR) – Main Document Canada's 2023 NIR – Additional Information Documents Canada's 2023 NIR – CRF Tables https://data-donnees.az.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/E-LULUCF/?lang=en: Forest land full time series (EN_Ch6_Tables_FullTimeSeries.xlsx); Underlying data for figures (EN_Ch6_Figures_UnderlyingData.xlsx) Note: the raw data are the properties of 13 jurisdictions, some are proprietary while others are open access.
Russia: Mukhortova L., Shchepashchenko D., Shvidenko A. (2020). Soil respiration database. DOI: 10.22022/ESM/10-2020.107. https://doi.org/10.22022/ESM%2F10-2020.107 Schepaschenko D., Chave J., Phillips O.L., Lewis S.L., Davies S.J., et al. (2019). A global reference dataset for remote sensing of forest biomass. The Forest Observation System approach. DOI: 10.22022/ESM/03-2019.38. https://doi.org/10.22022/ESM%2F03-2019.38 Schepaschenko D., Shvidenko A., Usoltsev V.A., Lakyda P., Luo Y., et al. (2017). A database of forest biomass structure for Eurasia. 10.1594/PANGAEA.871492. https://doi.org/10.1594/PANGAEA.871492 Schepaschenko D., Shvidenko A., Moltchanova E. (2018) Map of Russian forest for the year 2009 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6056054 Shvidenko A., Mukhortova L., Kapitsa E., Pyzhev A., Gordeev R., Fedorov S., Schepaschenko D. (2022). Dead wood in the forests of Northern Eurasia: field measurements database [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7455327 Schepaschenko D., Moltchanova E., Fedorov S., Karminov V., Ontikov P., Santoro M. (2020). Map of growing stock volume of Russian forests for the year 2014 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.3981198
Northern European countries: Data are included in the data archive https://doi.org/10.2737/RDS-2023-0051 Finland: https://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/ Norway: The National Forest Inventory (ssb.no) Sweden The Swedish National Forest Inventory | Externwebben (slu.se) Kauppi, P. E., Stål, G., Arnesson-Ceder, L., Sramek, I. H., Hoen, H. F., Svensson, A., ... & Nordin, A. (2022). Managing existing forests can mitigate climate change. Forest Ecology and Management, 513, 120186. https://doi.org/10.1016/j.foreco.2022.120186
The continental US and Alaska Interior: https://www.fia.fs.usda.gov/tools-data/ https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021
Temperate Europe (EU): *Open access NFI data:* France: https://inventaire-forestier.ign.fr/dataIFN/ Germany: https://bwi.info/Download/de/ Italy: https://www.inventarioforestale.org/en/accesso-ai-dati/ Netherlands: https://www.probos.nl/publicaties/overige/1094-bosinventarisaties

Spain: https://www.miteco.gob.es/es/biodiversidad/temas/inventarios-nacionales/inventario-forestal-nacional/cuarto_inventario.html

Aggregated data:
Albania: https://akpyje.gov.al/
Austria: https://waldinventur.at/#/
Belgium (Flanders): https://www.natuurenbos.be/beleid-wetgeving/natuurbeheer/bosinventaris
Belgium (Wallonia): http://iprfw.spw.wallonie.be/summary.php
Bulgaria: https://fri.bas.bg/en/#
Croatia: https://www.sumins.hr/en/projekti/motrenje-ostecenosti-sumskih-ekosustava-icp-forests-hr/
Republic of Cyprus: https://www.moa.gov.cy/moa/fd/fd.nsf/index_en/index_en?OpenDocument
Czech Republic: https://www.uhul.cz/portfolio/nil/?lang=en
Denmark: https://research.ku.dk/search/result/?pure=en/publications/danish-national-forest-inventory(1b6fa271-2ca6-4eac-8bb3-666c7edacecc).html
Estonia: https://www.stat.ee/en/find-statistics/statistics-theme/environment/forest
Hungary: https://nfi.nfk.gov.hu/
Ireland: https://www.gov.ie/en/publication/53ac8-national-forest-inventory-results-data-2022/
Latvia: https://www.silava.lv/en/research/active-projects/national-forest-inventory
Lithuania: https://www.silava.lv/en/research/active-projects/national-forest-inventory
Lithuania: https://amvmt.lrv.lt/lt/veiklos-sritys/nacionaline-misku-inventorizacija/
Luxembourg: https://environnement.public.lu/fr/natur/forets/L_Inventaire_Forestier_National.html
Poland: https://www.bdl.lasy.gov.pl/portal/wisl-en
Portugal: https://www.icnf.pt/noticias/inventarioflorestalnacional
Romania: https://roifn.ro/site/
Serbia: http://www.srpskosumarskoudruzenje.org.rs/index.php?option=com_content&task=view&id=219
Slovakia: https://www.forestportal.sk/odborna-sekcia-i/ekologia-a-monitoring/niml/
Slovenia: https://www.gozdis.si/Nacionalna-gozdna-inventura_1/
Switzerland: https://www.lfi.ch/index-en.php?lang=en
United Kingdom: https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/

China:

Yang C, Shi Y, Sun WJ, Zhu JL, Ji CJ, Feng YH, Ma SH, Guo ZD, Fang JY. 2022. Updated estimation of forest biomass carbon pools in China, 1977-2018. Biogeosciences, 19: 2989-2999. https://doi.org/10.5194/bg-19-2989-2022

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Fang JY, Yu GR, Liu LL, Hu SJ, Chapin FS. 2018. Climate change, human impacts, and carbon sequestration in China. Proceedings of the National Academy of Sciences of the United States of America, 115: 4015-4020. www.pnas.org/cgi/doi/10.1073/pnas.1700304115

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Japan:

https://www.rinya.maff.go.jp/j/keikaku/tayouseichousa/
https://www.ffpri.affrc.go.jp/pubs/bulletin/425/documents/425-2.pdf
https://www.maff.go.jp/j/tokei/kouhyou/mokuzai_zyukyu/
https://www.maff.go.jp/e/data/stat/96th/index.html

Australia: https://greenhouseaccounts.climatechange.gov.au/ https://www.dcceew.gov.au/climate-change/publications/national-inventory-reports
New Zealand: https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2021/
Korea, other Europe countries (Ukraine, Belarus, Georgia, Armenia, Azerbaijan, Turkey), other temperate countries (Mongolia, Kazakhstan): FRA country reports: https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/ Turkey: https://www.ogm.gov.tr/tr Note: except Turkey, other countries used FRA data.
India: https://fsi.nic.in/
Tropics (Southeast Asia, Africa, and South America): Brienen, R.J.W. et al. 2015. Long-term decline of the Amazon carbon sink. Nature 519, 344-348 (2015). DOI: 10.1038/nature14283 Data package: https://forestplots.net/data-packages/brienen-et-al-2015 Duque, A., Peña, M.A., Cuesta, F. et al. Mature Andean forests as globally important carbon sinks and future carbon refuges. Nat Commun 12, 2138 (2021). https://doi.org/10.1038/s41467-021-22459-8. Data package: https://datadryad.org/stash/dataset/doi:10.5061/dryad.59zw3r26f Hubau, W. et al. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579, 80-87 (2020). DOI: 10.1038/s41586-020-2035-0. Data package: https://doi.org/10.1038/s41586-020-2035-0 Qie, L., Lewis, S.L., Sullivan, M.J.P. et al. Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects. Nat Commun 8, 1966 (2017). https://doi.org/10.1038/s41467-017-01997-0 [plot data there in Electronic supplementary material: Supplementary Data 1]. Sullivan, M. et al. 2020. Long-term thermal sensitivity of Earth's tropical forests. Science 368, 869-874 (2020). DOI: 10.1126/science.aaw7578. Data package: https://forestplots.net/data-packages/sullivan-et-al-2020 Brown, S., Iverson, L.R., Prasad, A. & Liu, D. Geographical distribution of carbon in biomass and soils of tropical Asia forests. Geocarto International 4, 45-59 (1993). https://www.tandfonline.com/doi/abs/10.1080/10106049309354429 Henry, M. Valentini, R. & Bernoux, M. Soil carbon stocks in ecoregions of Africa. Biogeosciences Discuss. 6, 797–823 https://doi.org/10.5194/bgd-6-797-2009 FRA country reports: https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/
Mexico: FRA country reports: https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/ IPCC. *Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ Cook-Patton. S. et al, Mapping potential carbon capture from global natural forest regrowth. *Nature* 585, 545–550 (2020). https://www.nature.com/articles/s41586-020-2686-x
Central America: FRA country reports: https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/ IPCC. *Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* (https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/) (2019). Cook-Patton. S. et al, Mapping potential carbon capture from global natural forest regrowth. *Nature* **585**, 545–550 (2020). https://www.nature.com/articles/s41586-020-2686-x

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Tropical deforestation emissions: Houghton, R. and Castanho, A.: Annual emissions of carbon from land use, land-use change, and forestry 1850–2020 (V1), Harvard Dataverse [data set], https://doi.org/10.7910/DVN/U7GHRH (2023). Note: More detailed information can be available upon request.
Other South Asia countries (Afghanistan, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka): FRA country reports: https://www.fao.org/forest-resources-assessment/fra-2020/country-reports/en/

Table S2. Influences of changing environmental and land management factors on regional carbon sinks and densities over the last three decades (1990-2020).

Factors affecting regional forest carbon sink	Results and observations from this study – stock and stock-change	Factors for interpreting the results	Factors with less impacts, or unidentifiable impacts
Boreal forests			
Asian Russia	Total sink reduced by 42% over 3 decades, living biomass became a source in 2010s, increased deadwood sink, slightly decreased soil sink, increased carbon densities.	Disturbances (wildfires, insect outbreaks)(-), CO_2 fertilization (+),illegal logging)(-) (only uncounted logging, otherwise logging is counted in stock-change and HWP)	longer growing season (+), drier (-), warming (+/-)
European Russia	From 2000s to 2010s, total sink had a slight decrease. There was small decrease in living biomass sink, moderate increase in deadwood sink, moderate decrease in soil sink, increased C densities.	Wildfires (-), soil warming (-), CO_2 fertilization (+)	longer growing season (+), wetter climate (+) (which could buffer heat-drought)
Canada	Includes only managed forests in Southern Canada. The forest was C sources in 2000s and 2010s, and the source in 2010s double that in 2000s. in 2000s only living biomass was a source, while in 2010s living biomass, litter and deadwood all became sources, and the soil sink was reduced 35% compared to 2000s. Carbon density decreased slightly.	Disturbances (wildfires, insect outbreaks)(-), drier and hotter climate (-), soil warming (-)	longer growing season (+/-) (due to drier conditions it could be a negative factor), CO_2 fertilization (+) (other negative factors overwhelmed this effect as the forest was a C source)
Alaska Interior	Total sink reduced by 76% in 2010s vs. 1990s, living biomass sink decreased by 21%, while litter, deadwood and soil became C sources. Increased C densities.	Wildfires (-), soil warming (-), CO_2 fertilization (+)	longer growing season (+/-), drier climate (-)
European boreal	Total sink increased by 48%. Increased C density.	Adaptive management (+), longer growing season (+), CO_2 fertilization (+) (increased logging in the later 2010s was reflected in increased HWP). Illegal logging (-) not counted	Wetter climate (+)

Temperate forests			
United States	Total sink decreased by 11% over 3 decades, starting to decrease in 2000s by 10% and remaining similar sink to 2010s. Increased C densities.	Natural disturbances (-), aging (-), deforestation (-), CO_2 fertilization (+)	longer growing season (+), N deposition (+)
European temperate	Total sink decreased by 7% over 3 decades, having a slight increase in 2000s (5%) but 12% decrease in 2010s with 21% decrease in living biomass sink while 5% increase in soil sink. Increased C densities.	Natural disturbances (-), aging (-), CO_2 fertilization (+), increased forest areas (+)	longer growing season (+), N deposition (+)
China	Total C sink increased by more than 200% over 3 decades, doubled in 2000s and tripled in 2010s vs 1990s. Increased C densities.	Afforestation/reforestation in later 1980s and early 1990s (+), CO_2 fertilization (+)	longer growing season (+)
Japan	Total C sink decreased by 32%, starting from 2000s but greatly in 2010s (-29%). Increased C densities.	Aging (-), CO_2 fertilization (+)	Natural disturbances (-), longer growing season (+),N deposition (+)
Australia	Carbon sources in 1990s and 2000s, slight C sink in 2010s. Small increased C density in 2000, 2010 but a decrease in 2020.	Wildfires (-), deforestation (-), improved forest protection (+),CO_2 fertilization (+), replaced old growth by new forest (+ for sink, - for C density and stock)	drier (-), longer growing season (+/-), increased climate variability (+/-)
Tropical intact forests			
India	Total C sink decreased by 48% over 3 decades with 68% decrease in 2000s while 59% increase in 2010s vs 2000s. Increased C density in 2000, slightly decreased C densities in 2010 and 2020.	Illegal logging (-), wood fuel collection (-), forest protection (+), young forest (+ for sink, - for C density)	natural disturbances (-), CO_2 fertilization (+), warming (-), drier climate (-)
Southeast Asia	Continuously decreasing with total decreased C sink by 25% over 3 decades. Increased C densities.	Deforestation (-), illegal selective logging (-), CO_2 fertilization (+)	natural disturbances (-) warming (-), drier climate (-)
Africa	Continuously decreasing with total decreased C sink by 25% over 3 decades. Increased C densities.	Deforestation (-), illegal selective logging (-), wood fuel collection (-), CO_2 fertilization (+)	natural disturbances (-) warming (-), drier climate (-)
Mexico	Continuously decreasing with total decreased C sink by 7% over 3 decades, Increased C densities.	Deforestation (-), Illegal logging (-), drier climate (-), CO_2 fertilization (+)	natural disturbances (-), warming (-)

South America	Continuously decreasing with total decreased C sink by 42% over 3 decades. Increased C densities.	Deforestation (-), illegal selective logging(-), droughts (-), CO_2 fertilization (+)	Natural disturbances (-), warming (-)
Tropical regrowth forests			
India	Decreased by 70% over 3 decades, mostly in 2000s (-69%). Increased C densities except a slightly decrease in 2010.	Illegal logging (-), wood fuel collection (-), forest protection (+), CO_2 fertilization (+)	Natural disturbances (-) warming (-), drier climate (-)
Southeast Asia	Continuous increasing with total increased C sink by 55% over 3 decades, decreased C density in 2000, while increased densities in 2010 and 2020.	Expansion of regrowth forest areas (+), CO_2 fertilization (+), considerable replacement of intact forest by oil palm plantation in 1990s caused a C density decrease in 2000	Repetitive deforestation and illegal logging (-), warming (-), drier climate (-), other natural disturbances (-)
Africa	Continuous increasing with total increased C sink by 28% over 3 decades, increased C densities	Expansion of regrowth forest areas (+), CO_2 fertilization (+)	Repetitive deforestation and illegal logging (-), warming (-), drier climate (-), other natural disturbances (-)
Mexico	Continuously decreasing with total decreased C sink by 13%. Increased C densities.	Illegal logging (-), drier climate (-), CO_2 fertilization (+)	Natural disturbances (-), warming (-)
South America	Continuous increasing with total increased C sink by 35% over 3 decades, increased C densities.	Expansion of regrowth forest areas (+), CO_2 fertilization (+)	Repetitive deforestation and illegal logging (-), warming (-), droughts (-), other natural disturbances (-)

Table S3. Example showing the replacement of lower C density tropical regrowth for higher C density tropical intact forest decreases the mean carbon density of tropical forests and make the mean global C density maintain about same although each individual forest has increased C density.

Forest biomes/classes	Year	Carbon stock (Pg C)	Forest area (10^6 ha)	Carbon density (Mg C ha^{-1})
Tropical intact forest	1990	510.7	1796.6	284.3
	2020	393.2	1329.6	295.8
Tropical regrowth forest	1990	33.6	348.1	96.4
	2020	75.6	541.9	139.4
All tropical forests	1990	544.3	2144.7	253.8
	2020	468.8	1871.5	250.5
Boreal forest	1990	252.4	1134.9	222.4
	2020	264.9	1146.4	231.1
Temperate forest	1990	116.5	742.2	157.0
	2020	135.8	794.1	171.0
Global total forest	1990	913.2	4021.8	227.1
	2020	869.5	3812.0	228.1

Note: C density = carbon stock/forest area

Table S4. Assessment of factors that could affect carbon sink in the world's forests.

Factors influencing the global forest carbon sink	***Prospective influence from 2020 to 2050 (with positive/ negative/ uncertain overall impact on trend of forest carbon sink)***
Deforestation and forest degradation	Continued slowing trend in the tropics will reduce emissions from LU and LUC **(+)**
Forest harvesting	Increased demand for wood as products and bioenergy would reduce the age and C stock of existing forests, resulting in net emissions **(-)**. How the harvested wood is used – e.g. long-lived products or bioenergy, and what products are substituted by wood use, will affect the net impact on the atmosphere (?)
Natural disturbances and drought	Likely to increase significantly with rapidly changing climate, increasing emissions from intact forests worldwide **(-)**
Forest aging	Slower growth of older forests in some regions will reduce the C sink **(-)**
CO_2 fertilization	Will continue to increase growth but could saturate over the next few decades **(-)**
Reforestation/afforestation	Lack of unused land will reduce the area of regenerating forests and the global C sink **(-)**, countered by large efforts under way to increase areas of afforestation and reforestation **(+)**
Large-scale adoption of nature-based climate solutions	Could potentially reverse any projected decline in the baseline C sink, but the level of future mitigation activity is uncertain and requires significant and sustained investments **(+?)**
Worldwide food shortages	Global food supplies could be significantly reduced because of climate change and conflicts, reducing land available for expanding tree cover **(-)**

Table S5. Annual changes in forest C stock (Tg C year^{-1}) for whole ecosystem compared to when estimated soil sinks are excluded. Note that excluding the estimated soil sinks reduces the estimated global forest C sink totals by c. 400 Tg C year^{-1} but has minimal impact on the global and biome-level temporal trends.

	1990-1999				2000-2009				2010-2019			
Biome and country /region	Total Net C stock change	Uncertainty plus 100% uncertainty for soil sink* (±)	Net C stock change *without* soil sink	Uncertainty of total net stock change§ (±)	Total Net C stock change	Uncertainty plus 100% uncertainty for soil sink (±)	Net C stock change *without* soil sink	Uncertainty of total net stock change (±)	Total Net C stock change	Uncertainty plus 100% uncertainty for soil sink (±)	Net C stock change *without* soil sink	Uncertainty of total net stock change (±)
Boreal Forest[1]												
Asian Russia	345.2	121.2	239.7	59.6	334.6	119.5	225.3	48.2	199.2	98.4	103.5	22.8
European Russia	129.0	27.9	108.9	19.4	138.7	30.9	113.8	18.3	131.4	21.7	114.1	13.1
Canada	0.4	2.6	-2.1	0.1	-20.2	6.1	-22.9	4.5	-47.8	13.0	-49.6	12.9
Alaska Interior	4.5	1.4	4.5	1.4	0.7	0.2	0.8	0.2	1.1	1.3	2.3	0.3
European boreal[2]	23.3	7.0	23.9	7.0	25.1	8.2	23.2	8.0	34.8	10.8	31.8	10.4
Subtotal	*502.5*	*124.6*	*374.9*	*63.1*	*478.9*	*123.8*	*340.2*	*52.5*	*318.7*	*102.2*	*202.2*	*41.1*
Temperate Forest[1]												
United States[3]	205.1	22.2	204.1	22.2	184.0	20.0	186.1	19.9	181.9	19.7	182.3	19.6
European temperate[4]	125.9	19.4	120.6	18.7	132.3	22.4	124.3	20.9	116.6	21.7	104.7	18.1
Other Europe[5]	67.8	25.8	46.7	14.8	50.5	15.5	39.3	10.5	65.3	33.2	36.4	16.4
China	78.7	16.7	67.8	12.7	164.4	28.8	151.5	25.8	250.5	50.1	217.9	38.0
Japan	33.5	9.7	34.8	9.6	32.3	8.8	32.9	8.8	22.8	4.2	23.5	4.1
Korea	22.5	11.2	12.8	5.7	32.0	15.9	18.2	8.0	26.8	13.8	14.8	6.8
Australia	-20.2	7.9	-16.1	6.8	-14.4	5.9	-11.0	4.8	3.0	5.4	8.3	1.0
New Zealand	13.3	5.6	8.7	3.2	9.9	2.8	10.3	2.8	11.1	2.8	10.8	2.8
Other countries[6]	-0.4	0.3	-0.1	0.1	0.5	0.3	0.3	0.2	6.6	4.3	2.8	2.0
Subtotal	*526.2*	*46.1*	*479.2*	*37.4*	*591.6*	*48.4*	*551.9*	*42.2*	*684.7*	*68.8*	*601.6*	*50.0*
Tropical Intact Forest												
India	77.6	16.4	67.5	12.9	25.2	7.6	18.1	2.9	40.0	9.5	31.5	4.2
Other South Asia[7]	18.9	8.1	12.9	5.5	0.6	1.4	0.5	1.4	3.3	1.2	3.3	1.2
Southeast Asia	118.0	45.2	114.0	45.0	97.8	36.6	95.1	36.5	88.8	34.3	85.1	34.1
Africa	476.4	139.4	462.5	138.7	451.4	94.9	440.8	94.3	397.5	134.4	380.8	133.3
Mexico	22.5	6.3	21.7	6.2	21.7	6.0	20.9	6.0	20.9	5.8	20.1	5.7
Central America	9.9	2.7	9.6	2.7	7.0	1.9	6.8	1.9	5.6	1.6	5.4	1.5
South America	560.5	140.0	539.6	138.4	427.3	160.8	410.8	160.0	324.3	192.3	298.3	190.5
Subtotal	*1283.8*	*203.6*	*1227.9*	*201.6*	*1030.9*	*190.6*	*993.0*	*189.4*	*880.6*	*237.4*	*824.4*	*235.1*
Tropical Regrowth Forest												
India	16.8	4.9	16.8	4.9	5.3	4.3	1.5	1.9	5.1	2.1	3.4	1.3
Other South Asia[7]	5.2	2.4	4.0	2.1	1.0	0.6	0.5	0.3	0.9	0.9	0.2	0.4
Southeast Asia	235.6	109.5	206.6	105.6	313.6	131.2	274.8	125.4	364.5	158.0	319.3	151.4
Africa	439.3	181.8	371.9	168.8	515.6	172.8	436.6	153.6	560.9	212.6	474.9	194.5
Mexico	82.2	24.8	72.0	22.6	74.2	22.4	65.0	20.4	71.1	21.5	62.3	19.6
Central America	95.9	28.1	86.1	26.4	96.9	28.4	87.1	26.7	99.0	29.0	88.9	27.2
South America	398.4	168.3	357.7	163.3	452.6	217.4	406.5	212.4	538.3	227.5	483.8	220.9
Subtotal	*1273.4*	*273.5*	*1115.0*	*259.9*	*1459.1*	*309.3*	*1271.8*	*292.5*	*1639.8*	*351.1*	*1432.8*	*332.7*
All Tropical Forest												
India	94.4	17.1	84.4	13.8	30.5	8.7	19.6	3.4	45.1	9.7	35.0	4.0
Other South Asia[7]	24.2	8.5	16.9	5.8	1.5	1.5	1.0	1.4	4.0	1.5	3.4	1.2
Southeast Asia	353.6	118.5	320.6	114.8	411.4	136.2	369.9	130.6	453.4	161.7	404.3	155.2
Africa	915.7	229.1	834.4	218.5	967.0	197.1	877.3	180.3	958.4	251.5	855.7	235.8
Mexico	104.7	25.6	93.7	23.4	95.8	23.2	85.8	21.2	92.0	22.2	82.4	14.6
Central America	105.7	28.3	95.7	26.5	103.9	28.5	93.9	26.7	104.6	29.0	94.3	27.3
South America	958.9	218.9	897.3	214.0	879.9	270.4	817.3	265.9	862.8	297.9	782.1	291.7
Subtotal	*2557.2*	*340.9*	*2342.9*	*328.9*	*2490.0*	*363.3*	*2264.8*	*348.5*	*2520.5*	*423.8*	*2257.2*	*407.4*
Global Total	3588.7	*365.9*	3197.0	*337.0*	3560.5	*386.8*	3156.9	*354.9*	3523.8	*441.3*	3061.0	*412.5*

* The original uncertainties with additional uncertainties (100%) in the soil sinks. § The original uncertainties of total forest C sinks without removing uncertainties in the soil sinks

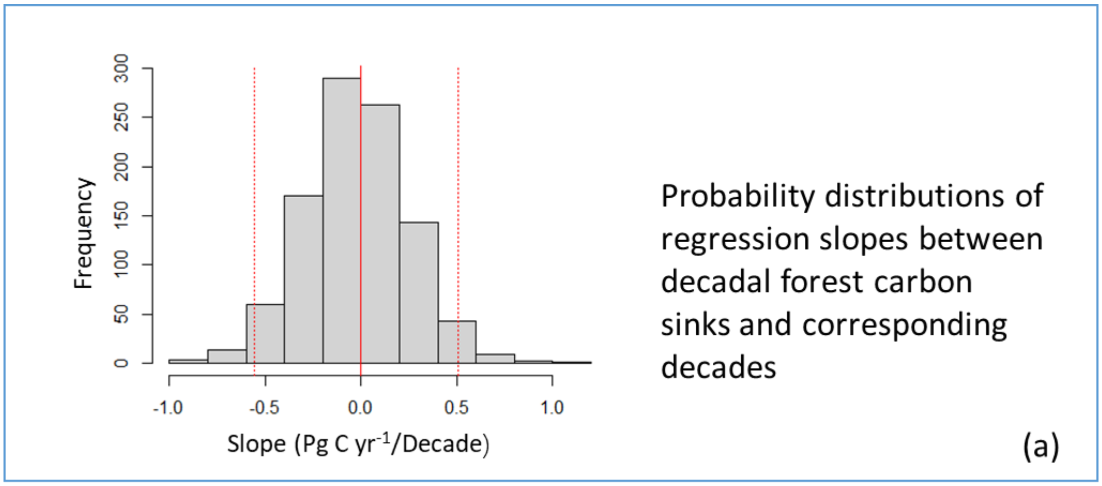
Table S6. Comparison of area estimates (Mha), this study and FAO Forest Resources Assessment 2020[15]

	Total Forest area 1990	Total Forest area 2000	Total Forest area 2010	Total Forest area 2020
Forest area used in this study	4021.8	3931.2	3873.8	3812.0
Forest excluded from C analysis				
Canadian unmanaged forests	121.6	121.5	121.4	121.3
Alaska interior unmanaged forests	8.7	8.7	8.7	8.7
West/Central Asia	61.5	63.0	65.7	66.2
Subtotal	191.8	193.2	195.8	196.2
Global Total, based on this study	4213.6	4124.4	4069.6	4008.2
Global Total, FRA 2020	**4236.4**	**4158.1**	**4106.3**	**4058.9**

Table S7. Comparison of estimates of tropical regrowth rates for above-ground biomass (AGB) and soil (Mg C ha^{-1} yr^{-1}).

Decade and source		SE Asia AGB	SE Asia soil	Africa AGB	Africa soil	S America AGB	S America soil
1990s	Cook-Patton[33] and this study*	2.86	0.42	2.22	0.42	3.54	0.42
	Houghton[43]	3.34	0.18	1.04	0.45	4.02	0.65
2000s	Cook-Patton[33] and this study*	2.85	0.42	2.22	0.42	3.56	0.42
	Houghton[104]	3.37	0.18	1.03	0.46	3.99	0.61
	IPCC[105]	3.50	--	2.30	--	3.60	--
	Pan et al.[35]	3.50	--	1.50	--	4.60	--
2010s	Cook-Patton[33] and this study*	2.84	0.42	2.22	0.42	3.58	0.42
	Houghton[43]	3.36	0.18	1.04	0.45	4.01	0.63
	IPCC[39] Rainforest (<20/>20)†	3.4/2.7	--	7.6/3.5	--	5.9/2.3	--
	IPCC[39] Moist forest (<20/>20)	2.4/0.9	--	2.9/0.9	--	5.2/2.7	--
	IPCC[39] Dry forest (<20/>20)	3.9/1.6	--	3.9/1.6	--	3.9/1.6	--

* Accounts for disturbance type and distribution of areas by ecozone.
† Two values represent stand ages less than 20 and more than 20 years.



Cohen's *d* (effect size, ES) = 0.01, 0.2, 0.5, 0.8, 1.2, 2.0 (very small, small, medium, large, very large, huge) for the maximum likelihood of difference; when ES <0.2, the difference can be ignored and is unlikely statistically significant.

1990s vs. 2000s: *d* = 0.04 (*n= 1000*)
2000s vs. 2010s: *d* = 0.04 (*n= 1000*)
1990s vs. 2010s: *d* = 0.08 (*n= 1000*)

(b)

Fig. S1. Examining the decadal trend of the global forest carbon sink. (a) Exploring the null hypothesis (H_0): $\mu = 0$, where μ represents the slopes (trend) of global forest C sinks against time periods. Monte-Carlo simulations were used to generate random samples using the mean value and standard deviation of each decadal C sink with 1000 repetitions (resulted three sample populations). A linear regression was computed between C sink estimates and corresponding decades (i.e. 1, 2, 3 for 1990s, 2000s, and 2010s to make a time series), for each of 1000 simulations, to construct a probability distribution and confidence intervals for the slopes. The dashed vertical red lines denote the 95% confidence interval. As these distributions overlap with zero (solid vertical red lines) with t-test for the slope of the regression $t < t_{0.95}$ (0.805 vs. 2.253), it failed to reject H_0. (b) Results of a Cohen' *d* analysis of effect size (ES), showing that the maximum likelihood of differences between the pairs of decadal forest C sinks can be ignored (ES<0.2) and is unlikely statistically significant.