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Pan, Y., Birdsey, R.A., Phillips, O.L. orcid.org/0000-0002-8993-6168 et al. (14 more authors) (2024) The enduring world forest carbon sink. Nature, 631. pp. 563-569. ISSN 0028-0836

https://doi.org/10.1038/s41586-024-07602-x

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The enduring world forest carbon sink

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Carbon dioxide uptake by terrestrial ecosystems is critical for moderating climate change[1]. To provide a ground-based long-term assessment of the contribution of forests to terrestrial uptake, we synthesized *in situ* forest data from boreal, temperate, and tropical biomes spanning three decades. We found that the carbon sink in global forests was steady at 3.6 ± 0.4 Pg year^{-1} in the 1990s and 2000s, and 3.5 ± 0.4 Pg year^{-1} in the 2010s. Despite global stability, our analysis reveals major biome-level changes. Sinks have increased in temperate (+30 ± 5%) and tropical regrowth (+29 ± 8%) forests due to increases in forest area, but decreased in boreal (-36 ± 6%) and tropical intact forests (-31 ± 7%) due to intensified disturbances and losses in intact forest area, respectively. Mass-balance studies suggest Earth's land sink has increased[2], implying an increase in the non-forest land carbon sink. The global forest sink is equivalent to almost half of fossil fuel emissions (7.8 ± 0.4 Pg C year^{-1}, 1990-2019). However, two-thirds of the sink's benefit has been negated by tropical deforestation (2.2 ± 0.5 Pg C year^{-1}, 1990-2019). While the global forest carbon sink has endured undiminished for three decades despite regional variations, it may weaken because of aging forests, continuing deforestation, and further intensification of disturbance regimes[1]. To protect the sink, land management policies must limit deforestation, promote forest restoration and improve timber-harvesting practices[1,3].

Atmospheric carbon dioxide (CO_2) concentration surpassed 420 ppm in 2023[4], and climate change is approaching potential tipping points that portend significant future impacts[1] without urgent actions[5,6]. While humanity has converged on the goal of achieving net zero greenhouse gas emissions by 2050[7], one of the most challenging elements is the need for large-scale "negative emissions" of up to 6 Pg C year^{-1} to compensate for the inability to eliminate all emissions from fossil fuels[8]. The land sector has capacity to sequester and store additional carbon because historically it has lost 180 Pg of stored C due to land use changes, and this former reservoir can be restored to some extent[5,9,10]. As forests are the dominant component of the land carbon sink[11], we need to know how much atmospheric carbon the world's forests have been sequestering, where it is stored, and whether recent trends are consistent with the desired strengthening of Earth's land sink.

Recent advances in remote sensing, modelling and computation can map and model Earth's land sinks at high temporal and spatial resolution yet have difficulty in generating long-term baselines and may diverge substantially in some regions and timeframes[12]. In contrast, the extensive ground-based and historical information from forest inventories and ecological studies permits analysis of forest dynamics (growth, harvest, mortality) by region or country, all ultimately based on tree-by-tree measurement of size, species and biomass. Whether regional[13] or global[11], these data provide a unique perspective on Earth's forests and how they are changing, and are highly complementary to top-down or model-driven approaches. The length, quantity and consistency of such records now permit a three-decade perspective on Earth's global and regional forest carbon balance and fluxes to span the entire period of land-use change, shifting forest dynamics and accelerating climate change since the IPCC's First Assessment Report in 1990[14].

We analyzed multiple decades of ground-based measurements by the global forest community (Table S1a, b, c), combined with forest area estimates based on remote sensing in national forest inventories and other types of land surveys, to estimate the recent magnitude, trend, impact factors, and locations of the global forest carbon sink. We constructed a global record of forest inventory measurements from 1990 through 2019, supplemented with high-quality data from long-term ecosystem monitoring sites. Our estimates of the forest land carbon sink are largely independent of other approaches including atmospheric CO_2 observations and inverse models[15], dynamic global vegetation models (DGVMs)[16], and mass-balance assessments[2]. The uncertainty of our estimated global forest carbon sink is ~0.4 Pg C year^{-1}, compared with other estimated terrestrial sinks[2] having uncertainties ranging from ~0.5-1.8 Pg C year^{-1}. We call for investment in specific research and monitoring priorities for reducing uncertainties in forest carbon assessments.

Global forest areas, C stocks, and sinks

The world's forest area declined by 5% from 1990 to 2020, from 4,022 Mha to 3,812 Mha (-210 Mha) (Extended Data Table 1). This net decline in forest lands is driven by losses in the tropics (-273 Mha, -13%). In contrast, temperate forest area increased (+52 Mha, +7%) while the boreal forest area was stable (+12 Mha, +1%). Within the tropics, 467 Mha (26%) of intact forest was lost but the area of regrowth forests expanded (+194 Mha, +56%).

The C stock in the world's forests in 2020 was 870 ±61 Pg C (Extended Data Table 2). In boreal, temperate, and tropical regrowth forests stocks increased by 74 Pg C over three decades. Meanwhile, deforestation reduced intact tropical forest carbon stocks by 149 Pg, while remaining intact tropical forests sequestered 32 Pg C to make up some of the losses (Extended Data Fig.1). Most of the 2020 global forest C stock is in live biomass (43%) and soils (45%), with smaller proportions in dead wood (8%) and litter (4%). The fraction of total C in living biomass increases towards the equator, while the proportion in soils shows the opposite pattern: boreal forests stored 20% of their C in living biomass and 64% in soils; temperate forests 38% in living biomass and 54% in soils; and tropical forests 57% in living biomass and 32% in soils. Total C stocks were highest in the tropics, lowest in temperate and intermediate in boreal forests.

The C density (Mg C ha^{-1}) increased from 1990 to 2020 in each biome (Extended Data Fig.2c). This suggests that global forests overall continued to gain C nearly everywhere, consistent with rising CO_2 concentrations increasing photosynthetic rates globally[17.18]. Other factors, such as warmer temperatures and increased N deposition may also enhance forest C densities regionally (Table S2). Nevertheless, the average global forest C density barely changed. This apparent paradox is due to the loss of high density intact tropical forests and their partial replacement by much lower C density regrowth forests, resulting in the average global forest C density staying near constant despite density increases within each category (Table S3).

The C sink in Earth's forests was estimated at 3.59 ±0.34, 3.57 ±0.36, and 3.53 ±0.41 Pg C $year^{-1}$ for the 1990s, 2000s to 2010s (Table 1), statistically stable over the decades (Supplementary Information, Fig. S1). Stable global totals mask large biome-scale changes: an increased sink in temperate (+30%) and tropical regrowth forests (+29%) but a decline in boreal (-36%) and tropical intact (-31%) forest sinks. Further, the C sink in global established forests– excluding tropical regrowth forests– declined by 19% from 2.32 ±0.21 to 1.89 ±0.24 Pg C $year^{-1}$ over 30 years (Table 1). After accounting for C emissions from tropical deforestation, the *net* C sink (Extended Data Box 1) in Earth's forests was still positive but showed no statistically significant trend (Fig. S1), being 0.93 ±0.63, 1.66 ±0.56 and 1.39 ±0.69 Pg C $year^{-1}$ in the 1990s, 2000s and 2010s (Table 1).

Forest C sinks by regions, biomes, and pools

Boreal forests

The boreal C sink declined from 508 ±63 Tg C year^{-1} to 324 ±41 Tg C year^{-1} from the 1990s to 2010s (Extended Data Table 3) and was strongly affected by Asian Russian forests that account for 57% of the boreal area (Extended Data Table 1). The C sink in Asian Russian forests declined by 42% over three decades, with the greatest reduction occurring in the late 2010s, primarily due to increased severity of wildfires, insect outbreaks, and increased logging both legal and illegal[19] (Fig. 1). Notably, living biomass contributed a large C sink in the 1990s (145 Tg C year^{-1}) but switched to a source in the 2010s (-20 Tg C year^{-1}); meanwhile the deadwood sink increased[20] by 44%. Alaska Interior managed forests were a small C sink in the 1990s, which was reduced by 76% in 2010s likely due to soil warming and increasing wildfires[21]. Canadian managed forests were about C neutral in the 1990s and small sources in the 2000s and 2010s (Extended Data Table 4). The much greater source from living biomass in 2000s (-55 Tg C year^{-1}) was caused by increased outbreaks of insects and wildfires[22]. In the 2010s, living biomass, deadwood and litter pools all became C sources while the soil sink was reduced by 35%, reflecting increased impacts of disturbances, warming, and droughts[22].

Unlike Canadian managed forests which have become drier, European Russia and European boreal forests have become wetter over the last half century[23]. Boreal forests of European Russia had a relatively stable multi-decadal C sink with a slight increase in the 2000s when agricultural lands that were abandoned in the 1990s returned to forest[24], followed by a slight decrease in 2010s likely due to increased harvesting and disturbances. However, our estimates show that the soil C sink decreased by 31% in the 2010s compared to the 2000s, possibly related to impacts of soil warming[25]. European boreal forests showed an increasing C sink over time resulting from improved management and growth enhancements due to CO_2 fertilization and lengthening growing seasons[26]. The latest forest inventory updates from

Finland[27] and Sweden[28] indicate a recent sink downturn responding to a combination of drought, changes in stand age structure and roundwood imports, and intensive harvests (Supplementary Information).

Temperate forests

The C sink in temperate forests was 526 ±37 Tg C $year^{-1}$ in the 1990s, increasing to 685 ±50 Tg C $year^{-1}$ in the 2010s (Extended Data Table 3). The major driver was the increase in China's forest area under national-scale afforestation and reforestation programs during the late 1980s and early 1990s, as those new forests reached their high productive stages in the 2000s and 2010s, increasing the sink by 86 Tg C $year^{-1}$ each decade[29].

The C sink in U.S. forests decreased by 10% in the 2000s compared to the 1990s and remained at that level in the 2010s (Fig. 1). In the 2000s, U.S. forests experienced increased natural disturbances and summer droughts[30]. Although the U.S. forest C sink did not recover fully in the 2010s, the rate of decline was reduced. The C sink in European temperate forests declined by 12% from 2000s to 2010s (Extended Data Table 3) probably because large forest areas planted in the 1950s approached C saturation as they matured[31]. More recently, central European forests suffered increasing bark beetle damage triggered by several years of droughts[32], which could lead to forests becoming C sources at the national level, although droughts alone did not seem to induce decreased growth[33].

In Japan, the C sink in living biomass decreased significantly in the 2010s, related to aging of forests planted in the 1960s[34] (Extended Data Table 3). Australian forests were C sources in the 1990s and 2000s and became merely neutral in the 2010s (Extended Data Table 3). This C source was due to extensive deforestation for agriculture, which declined in the recent decade because of legislative restrictions on clearing. Carbon was also lost from harvesting of native, high C density forests that were replaced by younger lower C density regrowth forests. Intensified droughts and wildfires in the 2000s and 2010s also contributed to increased net annual emissions.

Tropical intact forests

The C sink in tropical intact forests declined from 1284 ±202 Tg C year^{-1} in the 1990s to 881 ±235 Tg C year^{-1} in the 2010s (Extended Data Table 3), caused mainly by deforestation that reduced the remaining intact forest area by 26%. The greatest losses proportionally occurred in Southeast Asia, with 53% loss of intact forests (101 Mha) in the past 30 years, largely because of expansion of oil palm plantations[35]. The greatest losses by area were in South America (187 Mha, 22%) and Africa (175 Mha, 29%) (Extended Data Table 1). The C contained in deforested lands (149 Pg C) had different fates: about 45% was rapidly emitted to the atmosphere, 17% lost to processing harvested timber and for use of short-lived wood products such as paper, 2% was stored in long-lived wood products such as construction materials, and the remaining 36% continued to be stored on the land in the new land-use types, such as ranchland soils (Extended Data Fig. 1).

The tropical intact forest C sinks declined in Southeast Asia, Africa, and South America by 25%, 17% and 42% respectively (Extended Data Table 3). South America experienced the largest reduction because it lost most intact forest area, and because Amazon droughts contributed to increased tree mortality and slowing of tree growth rates[36,37,38]. Consequently, the 2010s sink in South American intact forests was less than two-thirds that in the 1990s (Fig. 1). The smallest decline in the forest C sink was in Africa, reflecting similar proportional losses of forest area but less impact of drought and warming on forest processes[37]. The decreased C sink in the Southeast Asia forest was mainly driven by forestland losses.

Tropical regrowth forests

The C sink in tropical regrowth forests increased from 1273 ±260 Tg C year^{-1} in the 1990s to 1640 ±333 Tg C year^{-1} in the 2010s. Despite occupying just 20% of the area of intact forest in the 1990s, these forests had a similar C sink (Extended Data Table 3) because their C sequestration rates are about five times higher, reflecting the early successional biomass accumulation phase of tropical forests. The regrowth C sink increased greatly in the 2000s and 2010s with expanded areas (Extended Data Table 1). Overall, the increasing tropical regrowth forest C sink balanced the declining sink in intact forests across 1990 to 2020, resulting in a near-constant tropical forest C sink of ~2.5 ±0.4 Pg C year^{-1} for three decades (Table 1). Although C sinks in both tropical intact and regrowth forests are large, high emissions due to deforestation and degradation counteracted nearly all of these remarkable sinks, making tropical forest lands almost carbon neutral (Extended Data Fig.3) with a small net sink/source between -0.1 and 0.6 Pg C year^{-1}, fluctuating with deforestation intensities in different decades (Table 1).

Necromass and Harvested Wood Products

We include estimates of C stock and sink in different components of forest necromass (non-living organic matter in standing and lying deadwood, litter, and soils) to enable reporting of complete forest ecosystem carbon budgets even though estimation of these pools has greater uncertainty. Necromass accounts for an average of 58% of total forest C stocks (514 ±52 Pg C), with proportions smallest in tropical forests (45%, 226 ±42 Pg C), intermediate in temperate forests (64%, 80 ± 9 Pg C), and greatest in boreal forests (80%, 207 ±10 Pg C) (Extended Data Table 2). The fraction of the C sink in necromass was 30% (781±154 Tg C year^{-1}) of that in living biomass globally, but varied greatly among biomes, averaging 184% (266 ±48 Tg C year^{-1}) in boreal forests but just 26% and 20% in temperate (109 ±16 Tg C year^{-1}) and tropical forests (406 ±105 Tg C year^{-1}) (Extended Data Table 3).

Harvested wood products (HWP) is defined as a C sink, related to the amount of timber harvested and the portion that remains in use or in solid waste disposal sites. Globally, only ~10% of C in harvested timber is counted as HWP[39] because about half of the wood is used for fuel and much of the rest lost during processing into wood products, followed by losses when products are discarded and decompose[3]. The average half-life of pulp and paper products is just two years while for sawnwood products it is 35 years[39]. The annual HWP increased by 10% over three decades to 0.21 Pg C year^{-1} in the 2010s, implying more wood harvested from forests. On average, HWP contributes only 6% of the global C sink (7%, 13% and 4% in boreal, temperate, and tropical forests respectively) (Extended Data Table 3), although this estimate does not fully account for the effects of illegal logging on wood harvesting fluxes.

Status of the global forest carbon sink

Our estimates show a large, long-term persistent sink of 3.56 ±0.37 Pg C year^{-1} in global forests since at least 1990 with a statistically insignificant change based on Monte-Carlo simulations and Cohen's *d* (Supplementary Information, Fig. S1). While stable overall, the contribution to this carbon sink by different forest biomes has fluctuated greatly over time. Within the tropics there has been a shift from equal contributions of intact and regrowth tropical forests in the 1990s, to 65% of the sink being in regrowth forests in the 2010s as the intact sink declined and the regrowth sink increased (Table 1). Boreal and temperate forests contributed similar C sinks in the 1990s, but by the 2010s the boreal sink had decreased to less than half the temperate sink (Table 1).

Carbon stock densities (Mg C ha^{-1}) in all forest biomes in all climate zones steadily increased (Extended Data Fig. 2c), showing that forest ecosystems across the planet continuously sequestered C, implying a universal growth factor, or several factors, enhancing forest sinks at continental scales. A suite of multidisciplinary evidence suggests that the global C sink persistence and C density increases were in part due to the CO_2 fertilization effect contributing to substantially increased photosynthesis[17,18], in addition to longer growing seasons in temperate and boreal regions[26]. These may have outweighed negative effects on forest C from global heating, changing rainfall patterns, and changes in the frequency and severity of natural disturbances in remaining forests[1,5].

Regional vulnerability of C sink and future prospects

The C sink in Earth's forests is vulnerable to deforestation, degradation, and disturbances triggered or intensified by climate change. In intact tropical forests, the foremost threats remain ongoing deforestation and degradation, the primary causes of the declining C sink (Extended Data Fig.1). More intense and frequent droughts have also killed millions of trees, contributing to a weaker C sink in Amazonia[37,40]. Given that the combined sink in intact and regrowth forest is stable, the sign of the net sink for tropical forests as a whole is largely determined by the rate of deforestation emissions. Only reducing deforestation and degradation will keep stored carbon out of the atmosphere and by protecting tropical forests we also protect their biodiversity and sink capacity in the future.

Boreal forests have experienced major impacts from climate change, including greater increases in temperature and variability than other regions[41]. Climate change has disrupted C dynamics in vegetation and soils, and exacerbated disturbances by wildfires, insect outbreaks, and droughts. The high C stock and sink in boreal forest necromass are threatened by increased decomposition rates and wildfires following dry conditions[42]. These impacts made Canadian forests a C source[22], while Asian Russian forests lost 42% of their sink strength over three decades, particularly in the late-2010s[25]. Future threats for boreal forest C dynamics also include northward shifting of bioclimatic zones that directly causes thawing of permafrost, triggering megafires such as occurred in 2020-2022, increased risk of large-scale pest outbreaks, and increased rates of legal and illegal logging, which all result in release of methane and CO_2 (Supplementary Information).

Temperate forests include Earth's most intensively managed forest ecosystems. The increased C sink resulted mainly from past tree planting in China[29]. Temperate forests that recovered on abandoned agricultural lands or heavily harvested forests in early-to-mid last century are now approaching the age at which growth rates begin declining, though growth trajectories and successional dynamics differ within the temperate forest biome[31,34,43]. Climate change has caused increases in frequency and intensity of natural disturbances, triggering intensified bark beetle outbreaks following drought in some European forests[32]. Additionally, increasing temperate zone tree harvests over the three decades (+17%) caused loss of stocks.

Although asynchronous regional dynamics ensured that the aggregate C sink in Earth's forests was almost constant, our analysis shows how biome- and continental-scale forest C sinks were susceptible to multiple environmental changes and timber harvesting. All these factors impact growth, mortality, and stocks and therefore future changes will affect the persistence and strength of the global forest C sink. With several strong positive and negative drivers (Table S4), each likely to develop differently among biomes and regions, the global forest C sink has an uncertain future. We therefore recommend carefully monitoring its future evolution.

Comparing estimates of land C sinks using different approaches

Our estimates for forests can be placed in the context of terrestrial sinks and sources estimated from the Global Carbon Budget (GCB)[2] (Fig. 2). Both GCB's mass-balance and the mean of 17 DGVMs' results estimated that the land ***gross*** C sink grew[44], meaning that the contribution of Earth's total forest C sink (~3.6 Pg C yr^{-1}) to the land ***gross*** sink has declined relatively from 75% in the 1990s to 65% in the 2010s (Extended Data Table 4). This also implies that non-forest lands have been progressively removing more carbon from the atmosphere (Fig. 2). Our results showing relatively stable global forest ***gross*** sinks contrast with most carbon model estimates which show C uptake is increasing across most forest biomes[44]. This means that the modelled future terrestrial C uptake by forests may be overestimated.

By contrast, over the three decades the global forest ***net*** sink (1.3 Pg C year^{-1}) amounted to 91% of the land ***net*** sink (1.4 Pg C year^{-1}) (Fig.2). The forest ***net*** sink we estimated thus compares closely to the ***net*** land sink independently estimated using DGVMs, of 0.9, 1.2 and 1.5 Pg C year^{-1} for the 1990s, 2000s, and 2010s respectively, and is broadly comparable with inverse model estimates and other methods[44]. Finally, while the magnitude of the global forest ***net*** sink is only 17% that of fossil fuel emissions, the forest ***gross*** C sink was of course much greater. The total three-decadal sink of 106.9 Pg C is equivalent to ~46% of fossil fuel emissions. Even for the 2010s the global forest C gain would have amounted to 37% of contemporary fossil fuel emissions had deforestation ceased (Extended Data Table 4).

Uncertainties, data gaps and future research priorities

Uncertainty of stock-change estimates varied by biome, with the largest uncertainties in tropical (+/- 27%) and boreal (+/- 13%) biomes, and the smallest in temperate biomes (+/- 7%) (Extended Data Table 3). Countries with well-established national forest inventories based on statistical sampling had the lowest reported uncertainty. Thus, additional ground measurements and monitoring are especially needed in tropical biomes and countries that currently lack statistical sampling; in soils and dead wood globally; and in areas affected by natural disturbances and logging. For future global analyses based on bottom-up approaches, we recommend several research and monitoring priorities:

1. Increased sampling of belowground biomass, dead wood, litter, and soil C. These have much greater uncertainties than aboveground biomass, although smaller impacts on the total uncertainty except boreal forests. For instance, if we had increased soil sink uncertainties to 100% in all biomes (Table S5), globally it would only increase uncertainty in the total C sink by about 1% because sinks in living biomass are the dominant components. Along with increased field measurements, scaling up to the region and biome should employ detailed forest type maps to represent the distinct and variable forest conditions that comprise the total forest areas.

2. Increased research and sampling of underrepresented tropical forests, such as Southeast Asian wetland forests and African dry forests, could be combined with better forest type maps to mitigate potential biases from uneven sampling. This would require broad-scale support and investment in long-term on-the-ground monitoring of tropical forest biomass, growth and mortality, distributed across all tropical forest types. The enhanced land monitoring would complement and greatly leverage investments in space-based forest monitoring, and reduce

uncertainties in data about changes and climate sensitivities of Earth's most productive and diverse biomes.

3. Better information about uncertainty of forest area estimates which mostly rely on remote sensing or remote-sensing based forest inventory statistics and are often reported without uncertainty information[45]. Uncertainties in forest areas are caused by inconsistent remote-sensing data processing methods and definitions of forests, and make up a considerable proportion of the uncertainty of C sink estimates.

Enhancing the forest C sink to help attain global C neutrality

Our results suggest that the single most important action for sustaining and increasing the forest C sink is to stop emissions from deforestation and degradation, along with protecting the large C stocks that have accumulated over centuries especially in boreal forest soils. Recovery of functions by degraded forests and lands offers additional opportunities for enhancing C sinks with many co-benefits such as protecting biodiversity[46]. The pathways for stopping global deforestation and degradation will rely on international cooperation such as UN's REDD+ program. Financial, legislative and other incentives are needed particularly in tropical countries. Deforestation-free supply chains and well-managed selective logging can all lower deforestation rates.

Our study demonstrates considerable impacts of large-scale reforestation and afforestation on enhancing C sinks, either through natural recovery or mandated actions. Some countries, such as the U.S., have lands suitable for afforestation or improved management, but historically low adoption rates (Extended Data Table 1). Tropical forest regrowth represents another significant opportunity to accumulate additional C on abandoned land. Declining C sink strength due to forest aging has become more common in some temperate zones[31,34], although most older forests maintain high C stocks in the absence of human disturbances and some remain productive for very long times[43]. In the future, management intensity and its effects on forest age dynamics may determine C sink trends of temperate forests.

Strategic planning will help to prioritize forest management approaches to minimize C emissions and maximize C uptake and co-benefits. For instance, adaptive and climate smart forestry practices[5] such as reduced-impact logging[47], fuel management to increase resistance to wildfires[48], optimizing tree species resilience after disturbances, and restoring old-growth characteristics can be highly effective[49]. Protecting C stocks is also essential. For example, our data show that tropical regrowth forests have high C sequestration rates but their recovering C densities take many decades to reach intact forest levels. So, replacing intact forests with regrowth forests having large C sinks but much lower C stocks and diminished biodiversity is highly imprudent.

Since long-lived HWPs store C but only represent ~10% of C in harvested timber, switching from short-lived products like fuelwood or pulpwood to long-lived sawnwood products could sequester additional C, provided total harvest volume does not increase and reduce ecosystem C stocks. Improving wood processing technologies to reduce waste[47], developing new long-lived materials, and recycling[50] may benefit a sustainable and circular economy as suggested by the IPCC[5]. Our estimates indicate 107 Pg C were sequestered from the atmosphere by global forests since 1990, equal to 46% of fossil fuel emissions. While 63% of this uptake was negated by tropical deforestation, the remaining forests helped slow climate change. The global forest sequestration rate of ~3.56 Pg C year^{-1} (~13 Gt CO_2-eq year^{-1}) for 1990-2019 provides a baseline for the IPCC's ambitious assessment[4] that Agriculture, Forestry and Other Land Use sectors have a combined potential to mitigate an additional 8-14 Gt CO_2-eq year^{-1} during 2020-2050. Mitigating and adapting to the climate crisis are defining challenges for humanity, and these goals cannot be achieved without both protecting the carbon stocks and sinks in Earth's forests and reducing emissions from fossil fuels.

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Figure Legends

Figure. 1. Carbon sinks/sources (Pg C year^{-1}) in the world's forests through the decades. Green bars represent established forests (boreal, temperate, and tropical intact forests), while brown bars represent tropical regrowth forests. Positive values (with downward bars) indicate C sinks, while negative values (with upward bars) show C sources. Detailed uncertainties of sink/source are shown in Extended Data Table 3. We grouped a few regions/countries shown in the detailed table to fewer categories in order to keep the graphic from getting too cluttered, including Europe (Europe temperate + Other Europe), Japan/Korea (Japan + Korea), South Asia (India + Other South Asia), and Mexico/Central America (Mexico + Central America) (see Extended Data Table 3).

Figure 2. Comparison and integration of inventory-based global forest carbon sink (-) and source (+) (Pg C year^{-1}) estimates with those from the Global Carbon Budget (GCB)[2]. E_{FOS}, S_{OCEAN}, E_{GLUC}, S_{GLAND}, and S_{NLAND} (blue) were estimated by or derived from GCB. S_{GFOR}, E_{DFOR}, S_{NFOR} (black) and differences (E_{GLUC}-E_{DFOR}, S_{GLAND}-S_{GFOR}) were estimated in this study. Our values for the global forest gross sink (S_{GFOR}) and tropical deforestation gross emissions (E_{DFOR}), when compared to GCB total land estimates, provide new ground-inventory constraints with which to derive global *non-forest land* LULC gross emissions and gross sink estimates for each decade since 1990 (see Extended Data Table 4 for further details).

Methods

Forest biomes and lands

Estimates of C stocks and stock changes are reported for forests partitioned into three biomes: boreal, temperate, and tropical (including subtropical); and by carbon component (living biomass, dead wood, litter, soil, and harvested wood products). Forests in boreal and temperate biomes include both "forest land remaining forest land" and reforested or afforested lands (collectively "new forests"), while tropical forests are separated into remaining forests (intact forests) and regrowth forests. The area of global forests used as a basis for estimating C stocks and sinks was ~4.0 billion hectares, representing 95% of the global forested lands[51] (Extended Data Table 1, Table S6). The 5% not covered are some remote forest areas including unmanaged forests in northern Canada and Alaska Interior, and some areas of west/central Asia with sparse forests, where we lacked credible ground data. We do not include non-forested peatlands or wetlands, or coastal mangrove forests which commonly contain high C in soil or sediments[52].

Definitions of forest carbon pools and stocks

We generally followed the definitions from Table 3.1.2 in the IPCC Good Practice Guidance[53]. Definitions of five main carbon pools are detailed in the Supplement: living biomass, dead wood, litter, soil organic matter, and harvested wood products.

Carbon stock – carbon contained in different carbon pools or in all carbon pools.

Carbon stock change (or C flux) – change in carbon stocks between time points, which can represent carbon gain (sink) or carbon loss (source).

Overview of data and calculation methods

<u>Sources of data used in this study</u>

This study covers three decades (1990s, 2000s and 2010s) with available data from 1990 to 2020 (Table S1a, S1b, S1c). Since our last study (for 1990-2007)[10], country-scale greenhouse gas (GHG) inventories in temperate and boreal countries/regions have expanded to include more countries and have been updated. Networks of sample plots in tropical regions of Amazonia, Africa, and Southeast Asia have expanded. Our data are not always consistent with what individual countries report to FAO or IPCC. We use FAO data as reported in FRA 2020[51] to establish the total forest area by country or region. These data are a credible source for trend information about forest area over decades and across geographies.

Accounting approaches to calculations for different forest regions/biomes

There are slightly different accounting approaches used in this paper because the available data have been developed and presented in different ways in inventories, country reports, and the literature. Estimates were harmonized between accounting systems by carefully defining land areas and matching these with the sources of data, and by adjusting reported estimates where necessary to account for known inconsistencies. Our calculation methods are summarized in Table S1 and described in more detail Supplementary Information.

Either the "**stock-change**" or the "**default**" approaches were used for boreal and temperate biomes, following the guidance from IPCC[53,54]. The stock change approach was also applied for several tropical countries or regions (only intact forests) including India, other South Asia countries, Mexico, Central America and Caribbean. If there is no land-use change, then the stock-change approach is nearly identical to estimating the land-atmosphere CO_2 flux, with the exception of "lateral transfers" of C which primarily include river erosion, transport, outgassing, and deposition; and harvested wood products. One exception is Canada, which reports C stock changes based on the "**gain-loss**" approach. The default approach commences with a single forest inventory and then adds C gains from forest growth and losses from harvest, fires and decomposition without confounding estimates through C transfers between land-use categories[53].

We accounted for harvested wood products (HWP) but not for other lateral transport, which may be responsible for a significant global C sink into coastal oceans from forests that is not reflected in the stock-change method. If there is land-use change, then the stock-change accounting overestimates the C uptake by forests in proportion to the area of afforestation during the period of change, because existing C stocks on new forest land (primarily soil C) appear instantaneously in the forest carbon inventory, transferred from the previous land use category. Conversely, the stock-change approach may underestimate C uptake by forests in proportion to the area of deforestation because existing soil C may be moved to a non-forest land category and appear as a loss of C from forest. We corrected for this apparent loss in our accounting.

For the tropics (Southeast Asia, Africa and South America), C sinks and sources (or net fluxes) were estimated using a "**flow**" approach because most tropical areas lack the repeated national-scale forest inventories that are the basis for the stock-change approach. This approach is similar to the IPCC "tier 2" methods[53] that multiply region-specific estimates of C density or change in C density times the associated areas represented by the region-specific estimates. For intact tropical forests (not affected by land use or change), fluxes were estimated from measured C stock changes on permanent sample plots, which is nearly equivalent to forest-atmosphere C exchange except for river transport and deposition of C. The approach allows accounting for C gains in forests, including some impacts of forest degradation affecting rates of C gains, but not C losses due to deforestation because C stored in deforested areas is accounted separately in our global budget (Extended Data Fig. 1).

The effects of land-use change and harvesting on C flux were estimated separately using a **bookkeeping** approach[55] that keeps track of ecosystem C emissions and harvested wood products from deforestation and logging, and ecosystem C uptake on regrowing forests.

Estimates of C stock changes pertain to "forest land remaining forest land" plus "afforested land" for boreal and temperate forests. For tropical intact and regrowth forests of Southeast Asia, Africa, and South America, and also for tropical regrowth forests of Mexico and Central America/Caribbean, changes in C density times the associated areas were used. Estimates of C stocks for specific years (Extended Data Table 2) pertain to the total area of forest land in the given year and therefore include C stocks lost because of deforestation, which are not included in Extended Data Table 3. Thus, it is not possible to consistently match the estimates between these two tables, which is particularly true for tropical intact forests – the only biome that has lost substantial forest area (Extended Data Table 1).

Forest area and area change

Area estimates (Extended Data Table 1) are from country-level forest inventories or reports based on forest inventories. Forest inventories typically use remote sensing combined with ground observations to estimate forest area and area changes following FAO forest definitions, excluding “other wooded land”. Where forest inventory data direct from countries are lacking, particularly in the tropics, FAO statistics were used to estimate total forest area for 1990, 2000, 2010, and 2020[51]. In some regions, particularly the tropics and Russia, the quality of data reported to FAO is poor and the protocols may be subject to change over time. Because tropical intact forests defined in this study are not the same as primary forests defined in FAO statistics (see the definition in Extended Data Box 1), we used the area estimates of tropical intact forests from published studies for Southeastern Asia, Africa, and South America[35]. The difference between total tropical forest from the FAO[51] and the area of tropical intact forest for these regions was assumed to be the area of tropical regrowth forest. We attempted to establish good consistency between the change in reported areas from the years of 1990, 2000, 2010, and 2020, and estimated areas of afforestation and deforestation from inventories, country reports, and analyses of emissions from land-use changes.

Carbon stocks and carbon stock changes

Where available, C stock and density estimates are from country-level forest inventories or reports based on national forest inventories (NFI). Most countries in temperate and boreal biomes have established NFIs with repeated measurement of permanent sample plots. Generally, sample plots are randomly located across all areas of the country, and measurements taken on those plots that are located on forest land. Thus, the inventory is an unbiased sample of the population of trees in the country, and the precision of estimates may be calculated. The re-measurement interval is typically between 5 and 10 years. At each sample plot, individual trees are selected for measurement of diameter, height, species, and condition. Re-measurement determines the basic tree population dynamics: growth, mortality, and harvest. Additional measurements may be taken to include understory vegetation, woody debris, litter, and soils. For some temperate or boreal countries where direct access to inventory data is not available, we used a biomass expansion factor (BEF) approach, which converts estimates of growing stock volume to estimates of biomass or C stocks. The measured data may be used to estimate the C stocks and C stock changes using a variety of country-specific methods (described in

Supplementary Information), but generally following guidelines provided by IPCC[53,54]. For example, the basic tree measurements of diameter and height are used to estimate tree biomass and carbon using allometric models and conventional statistical methods.

For tropical intact forests of Southeast Asia, Africa, and South America, we used data from repeated long-term measurements of networks of ecological research plots, upscaled to the regions to estimate biomass and other C pools for the region's forest areas[35,36,37]. For tropical regrowth forests, which lack sufficient ground-based data, we followed the bookkeeping approach[56] which is based on a literature review of regrowth rates and C stocks and knowledge of forest areas and conditions, averaged over different ecozones (tropical wet, moist and dry forests) for each region[57]. These methods are described in more detail in Supplementary Information.

The data from regions, countries or continents were aggregated to global biomes: boreal, temperate, and tropical forests. For countries and regions that do not allow access to original data, the data from the FRA regional reports[51] were used to fill the data gaps (Table S1b). Available data allowed C stock and area estimates to be compiled for 1990, 2000, 2010, and 2020, and annual changes in C stocks (sometimes referred to as "sink" if there was a C gain, and as "source" if there was a C loss) to be estimated for three time periods: 1990-1999, 2000-2009, and 2010-2019.

More data are available for live biomass and biomass changes than for other C pools. Some forest inventories and many ecological studies also collect and report data for dead wood and litter, though less consistently than for biomass; therefore, empirical models are often the source of estimates for these C pools. Inventories of forest soil carbon across the landscape are scarcer than inventories of biomass or other ecosystem C pools, and sampling methods include varying soil depths for sampling among regions and countries. There are existing soil surveys in different countries, but very rarely with periodic revisits and rarely associated with documented information about aboveground forest vegetation. To evaluate forest soil C change over time is particularly challenging because the formation and respiration of soil C is affected by various biological, environmental and geographical factors; and land-use history; and not always correlated with more easily observable vegetation traits. In almost every region, empirical modeling methods were used to combine data from soil surveys and field studies for developing soil C estimates.

Harvested wood products (HWP)

HWP is defined as a component of the C sink in this study and included in the C stock change category. Where available, estimates of carbon in HWP are from country level inventory reports. Otherwise, harvested roundwood data were derived from FAO annual statistics (see Supplementary Information). Generally, estimates of carbon in HWP account for its temporary exclusion from the atmosphere, which includes both the wood products in use and discarded wood products remaining in landfills or dumps. For countries that lacked reported estimates of HWP, we derived a simple conversion factor from the countries that did report: the ratio of C flux in HWP (Tg C year^{-1}) to the quantity of harvested roundwood (million m^{3}) according to FAO reports[51], which is 0.095.

Approaches to estimate uncertainty

We report the Standard Error (SE) for estimates of C stocks and changes in C stocks, using the 95% confidence level. Values presented as "y ± x" should be interpreted to mean that the authors are 95% certain the actual value is between y – x and y + x. The 95% boundary was chosen to communicate the high degree of certainty that the actual value was in the reported range and the low likelihood (5% or less) that it was outside that range. This characterization is not, however, a statistical property of the estimate, and should not be confused with statistically defined 95% confidence intervals.

We report uncertainty using two approaches depending on the availability of uncertainty estimates from data sources: quantitative estimates and expert opinion. Quantitative estimates are based on remote sensing and sampling combined with empirical models, using either error propagation methods or Monte Carlo simulation approaches to combine all C pools together, and including the uncertainty of area estimates. The expert opinion approach is based on that adopted by IPCC for reporting in global assessments (described in Supplemental Information). Quantitative estimates are more commonly available for data derived from national forest inventories or extensive sampling plot networks, whereas expert opinion is used where quantitative estimates are unavailable, a method which has been used in previous large-scale analyses[58]– see Supplementary Information for details. In applying these approaches, we ensured that estimates based on expert opinion were not overly optimistic compared with estimates from similar countries or regions that reported quantitative estimates.

Evaluating major uncertainties in different biomes and C components

We reported uncertainties for the aggregated sums of individual C pools (such as litter and deadwood) but not for each individual pool because this detailed information is not regularly included in the publicly available estimates, even though the uncertainty of each individual C pool is included in the aggregated estimates of carbon stocks and stock changes that are estimated using error propagation approaches.

Uncertainty estimates for stock change in boreal forests are ~+/- 13% and possibly more considering uncertainty of soil C estimates. The largest stock change by far is in Russian boreal forests, and the uncertainty is particularly significant because of the large sink estimated in this region. The main reasons for the uncertainty of boreal forest estimates involve incomplete sampling of large areas of Alaska, Canada, and Russia, combined with poor data on soil C and wildfires particularly in the Asian part of Russia.

Uncertainty estimates for stock change in temperate forests are about +/- 7% representing the lowest value among all biomes. This is mainly because most temperate countries have strong and repeated forest inventory sampling programs that cover most of the forest area. The greatest uncertainty in temperate forests is for changes in soil carbon, which is not monitored as easily or as often as the other carbon pools.

Uncertainty estimates for stock change in tropical intact forests are about +/- 27% in the most recent period, largely because the estimates are based on a relatively small number of intensively monitored sites whose data are individually quite accurate but not conducive to scaling because representation of the larger population of forests by the collection of sites is unknown. This uncertainty is particularly notable because the largest component of the global forest C sink is in tropical forests. The effects of disturbances, particularly drought, are difficult to quantify, and there is relatively little data about the C pools other than live biomass.

Uncertainty estimates for stock change in tropical regrowth forests are about +/- 20%, a little lower than estimates for intact forests. The area of tropical regrowth forests is not well known, and there is relatively little sampling done. The error estimates, based on expert opinion, probably underestimate the true uncertainty of this increasingly important component of the global budget.

The uncertainties of stock-change estimates for soil C, dead wood, litter, and HWP are high in boreal regions and the tropics. However, the size of the sink in these pools is relatively small compared with living biomass, except boreal forests, so the contribution to overall uncertainty is also small. As shown by uncertainty experiments (Table S5), while ignoring soil C sinks would reduce the estimated global forest C sink by ~400 Tg C year^{-1}, it would have minimal impact on the global and biome-level temporal trends. Increasing 100% uncertainties in soil sinks, the total C sinks in boreal, temperate and tropical forests increased their uncertainties by 15%, 2% and <1%, respectively, yet with error propagation it increased uncertainty in total global C sink by ~ 1%.

Additional sources of uncertainty are described in the Supplementary Information.

Assessing our approach vs. modeling/remote-sensing approaches

Remote-sensing and modeling estimates of the forest sector are subject to significant uncertainties and inconsistency between different studies[59,60,61], compared with ground data that are based on more standard definitions and protocols[51,53,54]. Different representations and complexity of regional ecological processes, and limited calibration with data for parameterization are often the cause for inconsistencies in model results[62,63]. Indeed, remote sensing and modeling approaches are dependent on summarized “standard” per-hectare biomass estimates derived from field studies. Ground data have improved significantly, and multiple carbon pools are more often measured and monitored. Our estimates represent a credible complement to the remote-sensing and model-based estimates used for the land part of the

Global Carbon Budget[1,43], with terrestrial data in GCB being based on an average of models[62,64]. It is important to use multiple methods to contrast and compare calculations in order to improve overall estimates of land C sinks.

Data availability

Data used for synthesis and analysis in this paper are derived from more detailed measurements and are fully contained in the spreadsheets with embedded formulas for access (https://doi.org/10.2737/RDS-2023-0051). Our results can be replicated beginning with these spreadsheets. The estimates used for tables and figures of the main text and Extended Data are also in the data repository. The data repository also includes original measurements of a few countries and the source data information for others with DOIs and websites for accessing original data. Because policies for data sharing vary from country to country, some sources include original measurement data from sampling with fully open access, while some do not include original data but rather aggregated data. Most original data are publicly available through direct access, while in a few cases where the data is not publicly available, requests from regional authors are needed. Full descriptions of regional datasets and estimation approaches, including links, are provided in Supplementary Information.

References of Method

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Acknowledgements

We thank Dr. G. Domke for the information of Interior Alaska. We thank K. McCullough for making the map in Fig.1. We thank Drs. S.P. Wang and J.P. Brown for helping statistical analyses of Fig. S1. We thank Hans Fredrik Hoen (NMBU) and Annika Nordin (SLU) and for leading data compilation in Norway and Sweden, respectively. For support in making this possible, we thank the U.S. Forest Service and the Embassy Science program (Y.P.); the Woodwell Climate Research Center (R.A.B. R.H, A.C.); the European Research Council (Advanced Grant 'TFORCES' GA291585), the Royal Society (International Collaboration Award, ICA\R1\180100), and NERC (NE/S011811/1 'ARBOLES') (O.L.P); National Natural Science Foundation of China (Grant # 31988102) (J.F.); JSPS KAKENHI (Grant # JP21H03580) (A.I., S.H.); JSPS KAKENHI (JP21H05318) (A.I.); EU projects (H2020-Verify, H2020 Superb) (G.-J.N., B.L.); the European Space Agency (CCI Biomass 4000123662/18/I-NB) and the European Union's Horizon Europe research and innovation programme (EYE-CLIMA 10108139) (A.S., D.S.); and the US Agency for International Development (Grant #. MTO 069018). This study is a product of the global forest carbon working group.

Author contributions

Y.P. and R.A.B. were lead authors, synthesized the data and drafted the manuscript; O.L.P, R.A.H. J.F. provided critical concepts and substantial editing; Y.P, R.A.B., O.L.P, R.A.H., J.F. P.K, H.K., W.A.K., A.I., S.L.L, G.-J.N, A.S. contributed primary datasets and analyses, led regional estimates and writing of the methods; S.H., B.L, A.C., D.S., and D.M. contributed regional estimates and methodology documentation. All authors contributed in writing, discussions, or comments.

Table 1. The global forest carbon sinks and source (Pg C year^{-1}) over 3 decades from 1990 to 2019.

Carbon sink and source in biomes	1990-1999	2000-2009	2010-2019	1990-2019 (mean)	1990-2019 (total, Pg C)
Boreal forest	0.51 ± 0.06	0.49 ± 0.05	0.32 ± 0.04	0.44 ± 0.05	13.18 ± 0.29
Temperate forest	0.53 ± 0.04	0.59 ± 0.04	0.68 ± 0.05	0.60 ± 0.04	18.02 ± 0.24
Tropical intact forest	1.28 ± 0.20	1.03 ± 0.19	0.88 ± 0.24	1.07 ± 0.21	31.95 ± 1.15
Tropical regrowth forest	1.27 ± 0.26	1.46 ± 0.29	1.64 ± 0.33	1.46 ± 0.30	43.72 ± 1.62
C sink in World forests[4]	3.59 ± 0.34	3.57 ± 0.36	3.53 ± 0.41	3.56 ± 0.37	106.88 ± 2.02
Global established forests (excluding tropical regrowth)	2.32 ± 0.21	2.11 ± 0.20	1.89 ± 0.24	2.11 ± 0.22	63.15 ± 1.21
Tropical intact forest	1.28 ± 0.20	1.03 ± 0.19	0.88 ± 0.24	1.07 ± 0.21	31.95 ± 1.15
Tropical regrowth forest	1.27 ± 0.26	1.46 ± 0.29	1.64 ± 0.33	1.46 ± 0.30	43.72 ± 1.62
All tropical forests	2.56 ± 0.33	2.49 ± 0.35	2.52 ± 0.41	2.52 ± 0.36	75.68 ± 1.99
Tropical deforestation gross emissions	-2.66 ± 0.53	-1.91 ± 0.43	-2.13 ± 0.56	-2.24 ± 0.51	-67.05 ± 2.79
Global forest net C sink	0.93 ± 0.63	1.66 ± 0.56	1.39 ± 0.69	1.33 ± 0.63	39.83 ± 3.45

Equations of global forest C fluxes:

$F_{\mathit{GLOBAL\ GROSS\ FOREST\ SINK}} = F_{\mathit{BOREAL}} + F_{\mathit{TEMPERATE}} + F_{\mathit{TROPICAL\ INTACT}} + F_{\mathit{TROPICAL\ REGROWTH}}$ (Eq. 1.1)

$F_{\mathit{ESTABLISHED\ FORESTS}} = F_{\mathit{BOREAL}} + F_{\mathit{TEMPERATE}} + F_{\mathit{TROPICAL\ INTACT}}$ (Eq. 1.2)

$F_{\mathit{ALL\ TROPICAL\ FORESTS}} = F_{\mathit{TROPICAL\ INTACT}} + F_{\mathit{TROPICAL\ REGROWTH}}$ (Eq. 1.3)

$F_{\mathit{GLOBAL\ FOREST\ NET\ SINK}} = F_{\mathit{GLOBAL\ FOREST\ GROSS\ SINK}} + F_{\mathit{TROPICAL\ DEFORESTATION\ GROSS\ EMISSION}}$ (Eq. 1.4)

Notes: the definitions of forest biomes and C fluxes in the table and equations refer to Extended Data Box 1.

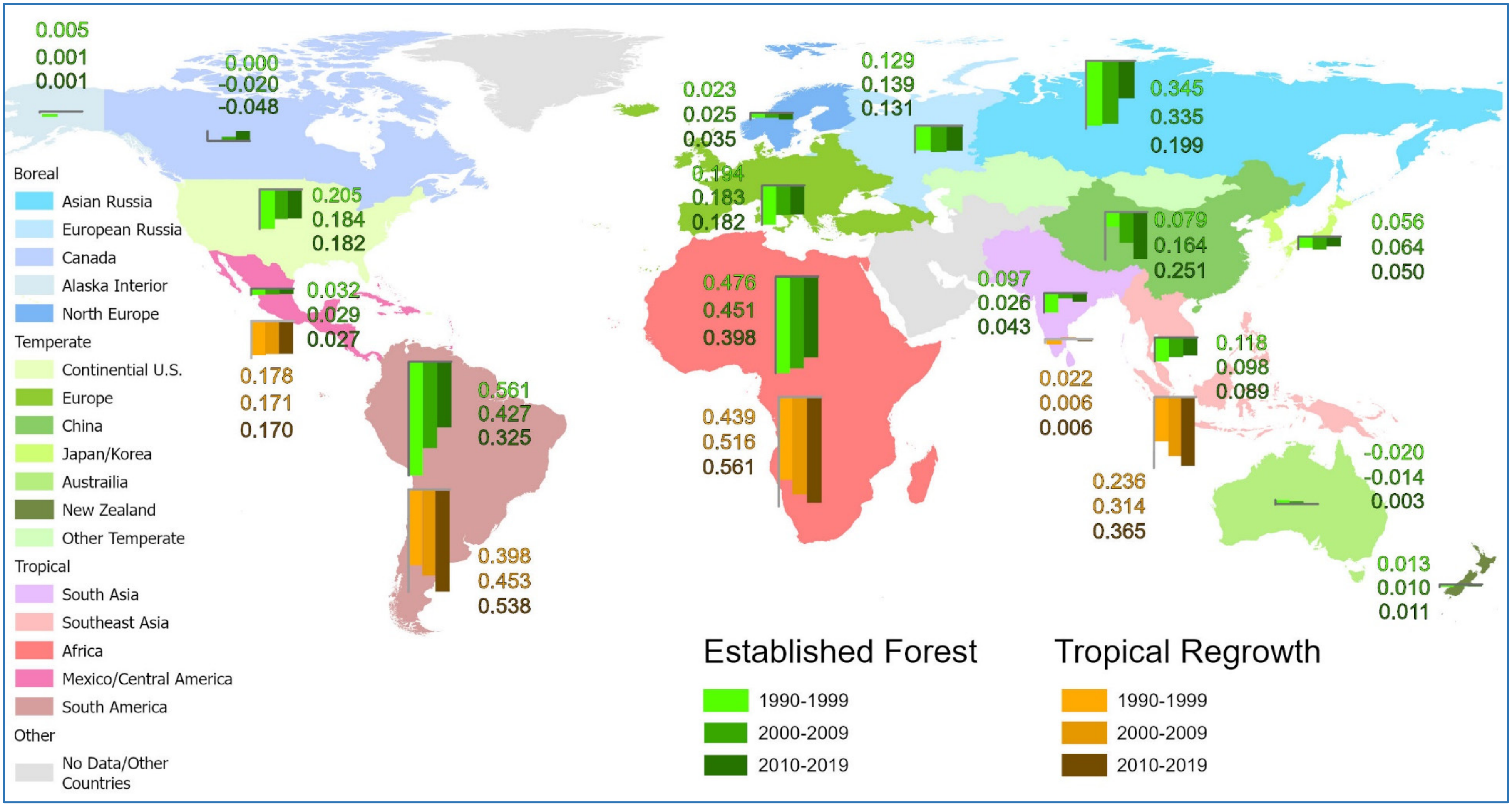
Extended Data Figure Legends

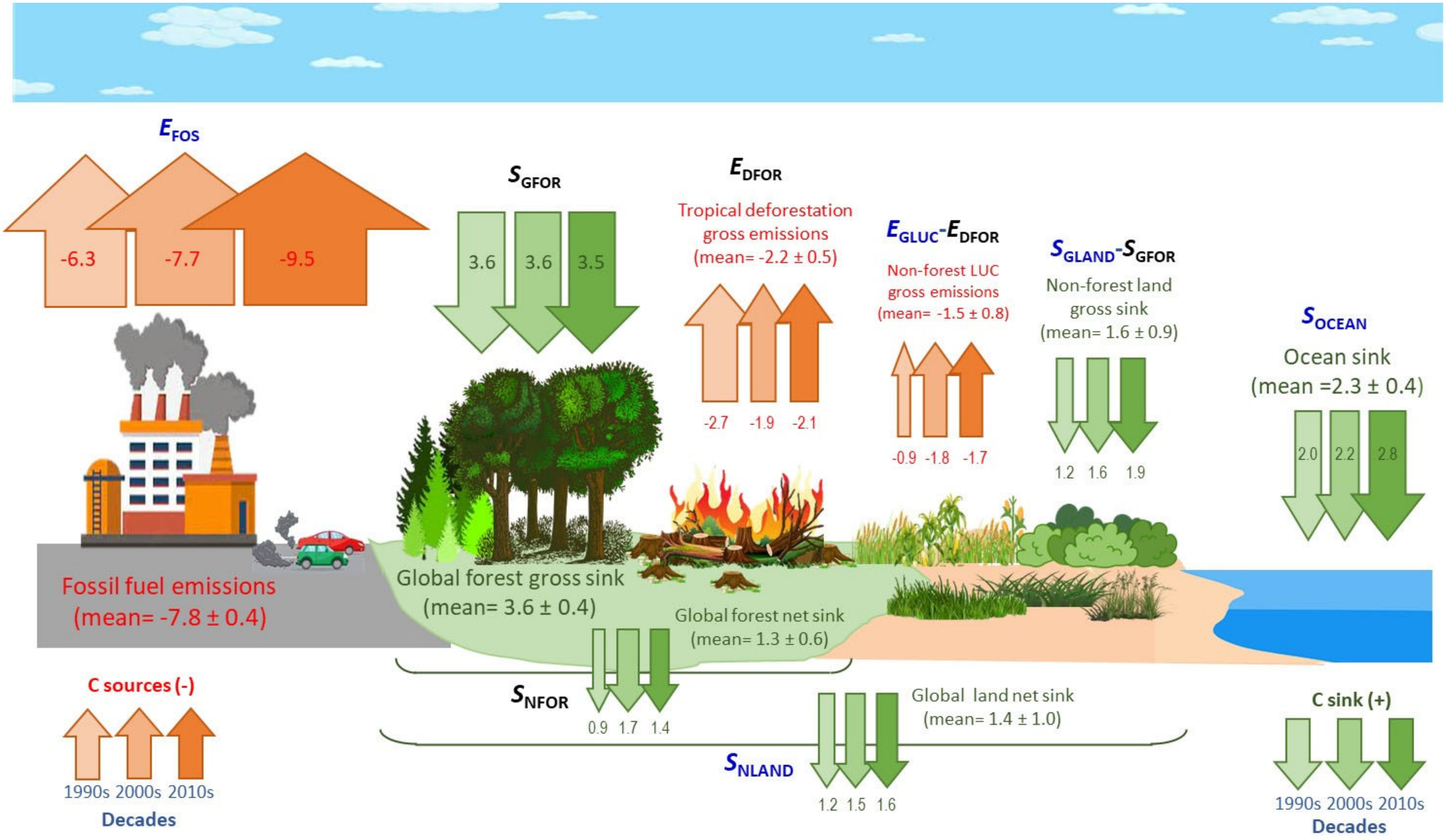
Extended Data Fig. 1. Why have tropical intact forests lost carbon stocks yet also provided a carbon sink? From 1990 to 2019, tropical intact forests that remain intact continued to sequester carbon by 32.0 Pg C (Table 1). Deforestation reduced the area of tropical intact forests by 467 Mha (containing C stocks of 149.4 Pg C). About 45% of C stocks in the deforested lands was emitted to the atmosphere shortly after the deforestation (mainly due to the slash-and-burning practice for agricultural land conversion), 36% was transferred to other land-uses such as agricultural lands (mostly as soil carbon), 17% was lost in processing harvested timber such as via wood shavings or stored in short-lived products such as fuelwood and paper, and 2% was retained in harvested wood products (HWP) such as long-lived construction materials. Because the remaining intact forests had provided a 32.0 Pg C sink, the net C stock loss from the intact forests was 117.5 Pg C.

Extended Data Fig. 2. Forest areas, carbon stocks, and carbon stock changes (fluxes) in the global forest and in forest biomes for the decades from 1990 to 2020: (a) forest areas; (b) carbon stocks; (c) carbon stock densities; (d) carbon stocks by pool; (e) carbon stock change (sinks); and (f) carbon stock change per hectare. The error bars represent standard deviations. For (a) we assumed 10% uncertainty in forest areas due to lack of documented uncertainty in remotely-sensed data; for (d) the uncertainty values of individual carbon pools were not included with most data sources, so we assumed that deadwood, litter and soil carbon pools have twice the uncertainty of the biomass pool, and estimated the uncertainty values of the individual carbon pools from the total carbon stock uncertainty. Uncertainties in the remaining charts are calculated based on data in Extended Data Table 2 and Extended Data Table 3.

Extended Data Fig.3. Carbon sinks and sources in global forests (Pg C year^{-1}) expressed as the mean annual rate across the full three-decadal period 1990 to 2019. Positive values represent carbon sinks, while negative (red) values carbon sources. Because carbon fluxes estimated in temperate and boreal forests were based on the "stock change" method, which included carbon gains and losses (from temporarily harvested forests), the C sink estimated was a net sink. Because carbon fluxes estimated in tropical forests were based on the "flux" method, C sinks estimated were gross sinks.

Tropical deforestation emissions were estimated by a book-keeping model. The tropical forest net sink, therefore, was the balance of C sinks and emissions (see Methods for concepts and details).


0.005
0.001
0.001
0.000
-0.020
-0.048
0.023
0.025
0.035
0.129
0.139
0.131
0.345
0.335
0.199
Boreal
Asian Russia
European Russia
Canada
Alaska Interior
North Europe
Temperate
Continental U.S.
Europe
China
Japan/Korea
Austrailia
New Zealand
Other Temperate
Tropical
South Asia
Southeast Asia
Africa
Mexico/Central America
South America
Other
No Data/Other Countries
0.205
0.184
0.182
0.194
0.183
0.182
0.079
0.164
0.251
0.056
0.064
0.050
0.032
0.029
0.027
0.178
0.171
0.170
0.476
0.451
0.398
0.097
0.026
0.043
0.118
0.098
0.089
0.022
0.006
0.006
0.561
0.427
0.325
0.439
0.516
0.561
0.236
0.314
0.365
-0.020
-0.014
0.003
0.398
0.453
0.538
0.013
0.010
0.011
Established Forest
1990-1999
2000-2009
2010-2019
Tropical Regrowth
1990-1999
2000-2009
2010-2019


E_{FOS}
-6.3
-7.7
-9.5
Fossil fuel emissions
(mean= -7.8 ± 0.4)
S_{GFOR}
3.6
3.6
3.5
Global forest gross sink
(mean= 3.6 ± 0.4)
E_{DFOR}
Tropical deforestation
gross emissions
(mean= -2.2 ± 0.5)
-2.7
-1.9
-2.1
E_{GLUC}-E_{DFOR}
Non-forest LUC
gross emissions
(mean= -1.5 ± 0.8)
-0.9
-1.8
-1.7
S_{GLAND}-S_{GFOR}
Non-forest land
gross sink
(mean= 1.6 ± 0.9)
1.2
1.6
1.9
S_{OCEAN}
Ocean sink
(mean =2.3 ± 0.4)
2.0
2.2
2.8
Global forest net sink
(mean= 1.3 ± 0.6)
S_{NFOR}
0.9
1.7
1.4
Global land net sink
(mean= 1.4 ± 1.0)
S_{NLAND}
1.2
1.5
1.6
C sources (-)
1990s 2000s 2010s
Decades
C sink (+)
1990s 2000s 2010s
Decades

Box 1. Definitions of forest lands, features, and fluxes

Forest – The definition of forest varies slightly from country to country, but generally follows the FAO FRA definition (see Supplementary Information). (Note: Our forest definition does not wholly conform to the "managed– unmanaged lands" distinction that is compulsory in the reporting to UNFCCC and as used in global integrated assessment models, since we cover a large portion of unmanaged forests.

Forest land remaining forest land – forests that do not undergo land-use change during the reporting period, including forests that are harvested and regenerate back to forest.

Afforestation – land that has changed from non-forest to forest.

Deforestation – land that has changed from forest to non-forest.

Boreal and temperate forests – comprised of "forest land remaining forest land" plus new forests (afforested land), including primary forests, secondary forests that have regrown back either from harvesting historically or more recently, harvested forests that have temporarily lost tree cover, and land afforested from other non-forest land-uses.

Tropical intact forest – tropical forest areas that have not been strongly modified structurally by human activities. Tropical intact forests include primary forests, alongside slightly modified forests to a maximum modification from low-intensity selective logging, and some long-established secondary forests.

Established forest – used in this study to represent existing forests including boreal, temperate, and tropical intact forests.

Tropical regrowth forest – tropical forests regrowing on abandoned lands that have been previously deforested or logged and used for agriculture or other non-forest land-use types.

Gross C sink– Total C sequestered by forest (or land).

Net C sink – the *gross C sink* subtracting C emissions from forest deforestation and degradation (or from land-use changes).

Extended Data Table 1. Area of forests (10^6 ha) and land-use change by biome, country, or region, and year

Biome and country /region	Total forest area, 1990 (10^6 ha)	Total forest area, 2000 (10^6 ha)	Total forest area, 2010 (10^6 ha)	Total forest area, 2020 (10^6 ha)	1990 -1999 Afforestation (10^6 ha)	1990 -1999 Deforestation (10^6 ha)	1990 -1999 Net change (10^6 ha)	2000 -2009 Afforestation (10^6 ha)	2000 -2009 Deforestation (10^6 ha)	2000 -2009 Net change (10^6 ha)	2010 -2019 Afforestation (10^6 ha)	2010 -2019 Deforestation (10^6 ha)	2010 -2019 Net change (10^6 ha)
Boreal Forest[1]													
Asian Russia	650.7	652.6	658.1	651.9	3.000	0.100	2.900	3.712	0.220	3.492	2.132	0.130	2.002
European Russia	170.7	173.3	177.6	181.8	3.201	0.100	3.101	3.596	0.130	3.466	3.028	0.120	2.908
Canada	226.9	226.5	226.0	225.5	0.082	0.579	-0.497	0.032	0.519	-0.487	0.009	0.544	-0.535
Alaska Interior	24.5	24.5	24.5	24.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
European boreal[2]	62.1	62.7	62.7	62.7	0.100	0.300	0.070	0.165	0.037	0.128	0.056	0.030	0.030
Subtotal	***1134.7***	***1139.4***	***1148.8***	***1146.7***	***6.308***	***0.552***	***5.756***	***7.505***	***0.906***	***6.599***	***5.225***	***0.824***	***4.401***
Temperate Forest[1]													
United States[3]	257.1	257.4	257.4	257.0	1.327	1.294	0.033	1.466	1.474	-0.008	1.399	1.721	-0.322
European temperate[4]	104.5	110.7	116.2	119.0	4.510	0.745	3.765	3.641	0.918	2.723	2.542	0.923	1.619
Other Europe[5]	40.9	42.0	43.4	45.0	0.797	0.139	0.658	0.431	0.51	0.280	0.517	0.230	0.286
China	139.7	142.8	163.5	174.1	44.349	41.227	3.122	40.295	19.587	20.708	16.372	5.778	10.594
Japan	25.2	25.1	25.1	25.0	0.488	0.577	-0.092	0.309	0.350	-0.044	0.208	0.250	-0.043
Korea	6.6	6.5	6.4	6.3	0.000	0.075	-0.075	0.000	0.089	-0.089	0.000	0.100	-0.100
Australia	134.4	132.7	131.1	134.1	0.633	0.155	0.478	3.085	6.523	-3.438	4.358	4.221	0.136
New Zealand	9.4	9.9	9.8	9.9	0.633	0.155	0.478	0.178	0.180	-0.002	0.120	0.076	0.045
Other countries[6]	17.5	17.4	17.3	17.6	0.153	0.246	-0.093	0.503	0.657	-0.155	0.794	0.433	0.362
Subtotal	***742.2***	***751.0***	***776.4***	***794.1***	***54.504***	***50.888***	***3.616***	***49.909***	***29.952***	***19.957***	***26.312***	***13.755***	***12.557***
Tropical Intact Forest													
India	56.0	59.5	60.7	63.0	0.749	0.384	0.365	0.820	0.630	0.191	1.870	1.337	0.533
Other South Asia[7]	14.0	15.1	14.6	14.3	0.284	0.076	0.208	0.301	0.053	0.249	0.110	0.095	0.015
Southeast Asia[8]	190.6	136.9	118.4	90.1	10.670	30.240	-19.570	11.203	13.572	-2.369	2.685	10.316	-7.631
Africa	600.2	531.8	477.8	425.5	7.233	24.080	-16.847	8.317	23.144	-14.828	4.304	21.424	-17.121
Mexico	39.9	34.8	32.5	32.0	0.465	0.686	-0.221	0.281	0.425	-0.144	0.127	0.377	-0.250
Central America	10.7	9.2	7.7	6.1	0.095	1.137	-1.042	0.089	0.924	-0.835	0.196	0.603	-0.406
South America	885.2	817.2	756.3	698.5	6.813	58.405	-51.592	14.325	66.815	-52.491	5.559	31.639	-26.080
Subtotal	***1796.6***	***1604.6***	***1468.1***	***1329.6***	***26.309***	***115.008***	***-88.699***	***35.335***	***105.562***	***-70.226***	***14.850***	***65.791***	***-50.941***
Tropical Regrowth Forest													
India	8.0	8.1	8.8	9.2	na	na	na	na	na	na	na	na	na
Other South Asia	2.0	2.0	2.1	2.1	na	na	na	na	na	na	na	na	na
Southeast Asia	53.1	85.2	99.5	116.1	na	na	na	na	na	na	na	na	na
Africa	142.6	178.2	198.2	211.1	na	na	na	na	na	na	na	na	na
Mexico	30.7	33.6	34.4	33.7	na	na	na	na	na	na	na	na	na
Central America	23.2	23.4	23.5	24.2	na	na	na	na	na	na	na	na	na
South America	88.5	105.4	113.9	145.7	na	na	na	na	na	na	na	na	na
Subtotal	***348.1***	***436.1***	***480.4***	***541.9***									
All Tropical Forest													
India	63.9	67.6	69.5	72.2	0.749	0.384	0.365	0.820	0.630	0.191	1.870	1.337	0.533
Other South Asia	16.0	17.2	16.8	16.4	0.284	0.076	0.208	0.301	0.053	0.249	0.110	0.095	0.015
Southeast Asia	243.7	222.1	217.9	206.2	10.670	30.240	-19.570	11.203	13.572	-2.369	2.685	10.316	-7.631
Africa	742.8	710.0	676.0	636.6	7.233	24.080	-16.847	8.317	23.144	-14.828	4.304	21.424	-17.121
Mexico	70.6	68.4	66.9	65.7	0.465	0.686	-0.221	0.281	0.425	-0.144	0.127	0.377	-0.250
Central America	34.0	32.6	31.2	30.3	0.095	1.137	-1.042	0.089	0.924	-0.835	0.196	0.603	-0.406
South America	973.7	922.6	870.2	835.2	6.813	58.405	-51.592	14.325	66.815	-52.491	5.559	31.639	-26.080
Subtotal	***2144.7***	***2040.6***	***1948.4***	***1871.5***	***26.309***	***115.008***	***-88.699***	***35.335***	***105.562***	***-70.226***	***14.850***	***65.791***	***-50.941***
Global Total	**4021.8**	**3931.2**	**3873.8**	**3812.0**	**87.196**	**166.975**	**-79.779**	**92.749**	**136.419**	**-43.670**	**46.387**	**80.370**	**-33.983**

Note: [1] Includes carbon stock for the reporting year on "forest land remaining forest land" and "new forest land" (afforested land).

[2] Europe (boreal) includes Norway, Sweden, and Finland.

[3] Excluding part of Interior Alaska and Hawaii.

[4] Europe (temperate) includes European countries (EU-28) Albania, Bosnia Herzegovina, Serbia, Switzerland, except for Norway, Sweden, and Finland.

[5] Other Europe includes Ukraine, Belarus, Georgia, Armenia, Azerbaijan, and Turkey.

[6] Other countries include Mongolia and Kazakhstan.

[7] Other South Asia includes Afghanistan, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka

[8] Southeast Asia includes Indonesia, Malaysia, Philippines, Vietnam, Cambodia, Thailand, Myanmar, Laos.

Extended Data Table 2. Forest carbon stocks (Pg C) by biome, country, or region for 1990, 2000, 2010, and 2020.

Biome and country /region	1990							2000							2010							2020						
	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncertain -ty of total C stock (±)	Carbon density (MgC ha^{-1})	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncertain -ty of total C stock (±)	Carbon density (MgC ha^{-1})	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncertain -ty of total C stock (±)	Carbon density (MgC ha^{-1})	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncertain -ty of total C stock (±)	Carbon density (MgC ha^{-1})
Boreal Forest[1]																												
Asian Russia	24.1	8.8	7.2	104.7	**144.8**	6.8	222.5	25.6	9.4	7.5	105.8	**148.3**	6.7	227.2	26.8	10.0	7.9	106.9	**151.6**	6.2	230.4	26.6	10.8	8.2	107.8	**153.4**	6.5	235.3
European Russia	9.1	2.5	1.5	25.4	**38.5**	2.2	225.5	9.8	2.8	1.6	25.7	**39.9**	2.1	230.2	10.5	3.0	1.7	25.9	**41.1**	2.0	231.4	11.0	3.4	1.8	26.0	**42.2**	2.2	232.1
Canada	13.3	4.6	10.7	18.6	**47.3**	7.1	208.3	13.2	4.5	10.9	18.6	**47.2**	7.1	208.2	12.6	4.6	10.9	18.7	**46.8**	7.0	207.1	12.4	4.5	10.7	18.7	**46.3**	6.9	205.2
Alaska Interior	0.5	0.2	1.1	5.6	**7.4**	2.3	300.3	0.5	0.2	1.1	5.6	**7.4**	2.3	302.2	0.6	0.2	1.1	5.6	**7.4**	2.3	302.0	0.6	0.2	1.1	5.6	**7.4**	2.3	302.3
European boreal[2]	2.2	0.2	0.3	11.71	**14.4**	2.9	232.4	2.3	0.2	0.4	11.7	**14.6**	2.9	232.4	2.5	0.3	0.4	11.8	**14.9**	3.0	238.4	2.8	0.4	0.4	12.0	**15.6**	3.1	248.6
Subtotal	***49.2***	***16.3***	***20.9***	***166.0***	***252.4***	***10.7***	***222.4***	***51.4***	***17.1***	***21.4***	***167.4***	***257.3***	***10.6***	***225.8***	***53.0***	***18.0***	***21.9***	***168.9***	***261.8***	***10.3***	***227.9***	***53.4***	***19.3***	***22.2***	***170.0***	***264.9***	***10.5***	***231.1***
Temperate Forest[1]																												
United States[3]	14.0	1.9	2.7	27.2	**45.8**	4.9	178.1	15.4	2.2	2.7	27.2	**47.5**	5.1	184.5	16.7	2.4	2.8	27.2	**49.1**	5.3	190.9	18.2	2.7	2.8	27.2	**50.9**	5.5	198.1
European temperate[4]	5.7	0.2	0.7	5.6	**12.2**	2.5	116.4	6.2	0.2	0.7	5.1	**12.2**	2.4	110.0	7.8	0.4	0.8	6.7	**15.7**	3.1	135.4	8.1	0.5	0.8	6.9	**16.4**	2.9	137.8
Other Europe[5]	1.6	0.0	0.3	2.1	**3.9**	0.7	96.0	2.0	0.0	0.3	2.3	**4.6**	0.8	109.0	2.3	0.0	0.3	2.4	**5.1**	0.9	116.6	2.6	0.0	0.4	2.7	**5.7**	1.0	126.4
China	5.4	0.4	0.5	14.6	**20.9**	1.7	149.6	5.9	0.4	0.5	15.0	**21.8**	1.7	152.7	7.1	0.5	0.5	17.3	**25.4**	2.0	155.4	8.0	0.5	0.5	18.6	**27.6**	2.1	158.5
Japan	1.8	0.1	0.1	3.6	**5.7**	2.1	224.4	2.1	0.1	0.1	3.6	**5.9**	2.1	235.1	2.3	0.1	0.1	3.6	**6.1**	2.1	244.2	2.4	0.1	0.1	3.6	**6.2**	2.1	247.8
Korea	0.1	0.0	0.0	0.1	**0.3**	0.1	39.4	0.3	0.0	0.0	0.2	**0.5**	0.1	74.1	0.4	0.0	0.0	0.3	**0.8**	0.2	124.3	0.5	0.0	0.0	0.5	**1.0**	0.3	166.2
Australia	8.4	1.6	0.6	11.5	**22.1**	7.4	164.4	8.4	1.6	0.6	11.4	**22.0**	7.4	165.8	8.3	1.6	0.6	11.3	**21.8**	7.3	166.3	8.3	1.6	0.6	11.4	**21.9**	7.3	160.0
New Zealand	1.6	0.2	0.1	0.9	**2.8**	0.4	300.7	1.7	0.2	0.1	0.9	**3.0**	0.4	299.6	1.8	0.2	0.1	0.9	**3.0**	0.5	306.9	1.8	0.2	0.1	0.9	**3.1**	0.5	310.7
Other countries[6]	0.7	0.1	0.3	1.5	**2.7**	0.6	151.7	0.7	0.1	0.3	1.5	**2.7**	0.6	152.3	0.7	0.1	0.3	1.5	**2.7**	0.6	153.9	0.7	0.1	0.3	1.6	**2.7**	0.7	154.5
Subtotal	***39.6***	***4.5***	***5.4***	***67.1***	***116.5***	***9.7***	***157.0***	***42.8***	***4.8***	***5.4***	***67.3***	***120.3***	***9.8***	***160.2***	***47.8***	***5.4***	***5.6***	***71.3***	***130.0***	***10.2***	***167.4***	***51.0***	***5.8***	***5.6***	***73.4***	***135.8***	***10.1***	***171.0***
Tropical Intact Forest																												
India	2.1	0.0	0.1	3.3	**5.5**	1.4	97.7	2.7	0.0	0.1	3.4	**6.2**	1.5	104.2	2.7	0.0	0.1	3.5	**6.3**	1.5	103.5	2.8	0.0	0.1	3.6	**6.5**	1.5	103.2
Other South Asia[7]	1.3	0.0	0.0	0.5	**1.9**	0.4	134.1	1.4	0.0	0.0	0.6	**2.1**	0.5	141.9	1.4	0.0	0.0	0.6	**2.1**	0.5	143.9	1.4	0.0	0.0	0.6	**2.1**	0.5	146.1
Southeast Asia[8]	45.8	8.5	0.7	17.3	**72.3**	9.4	379.5	33.7	6.2	0.5	12.5	**52.9**	7.2	386.7	29.9	5.5	0.5	10.8	**46.6**	6.6	393.8	23.3	4.2	0.4	8.3	**36.2**	5.4	402.0
Africa	85.4	18.8	1.3	64.7	**170.3**	48.3	283.7	79.4	17.2	1.3	57.5	**155.3**	44.2	292.1	74.9	15.9	1.2	51.8	**143.8**	40.6	300.9	69.6	14.5	1.1	46.3	**131.6**	37.5	309.2
Mexico	1.6	0.2	0.1	2.6	**4.5**	0.6	113.4	1.4	0.1	0.1	2.3	**3.9**	0.5	113.4	1.5	0.1	0.1	2.2	**3.9**	0.5	118.4	1.5	0.1	0.1	2.1	**3.8**	0.5	118.4
Central America	1.7	0.3	0.0	1.0	**3.1**	0.4	285.2	1.5	0.3	0.0	0.8	**2.7**	0.3	293.0	1.3	0.2	0.0	0.7	**2.3**	0.3	300.1	1.1	0.2	0.0	0.6	**1.9**	0.2	308.9
South America	142.6	26.9	2.6	81.1	**253.2**	32.2	286.0	136.2	25.4	2.5	75.1	**239.1**	31.1	292.6	129.4	23.9	2.4	69.6	**225.4**	46.4	298.0	121.9	22.4	2.3	64.6	**211.2**	44.7	302.3
Subtotal	***280.4***	***54.7***	***5.0***	***170.6***	***510.7***	***58.9***	***284.3***	***256.3***	***49.2***	***4.6***	***152.2***	***462.4***	***54.5***	***288.2***	***241.1***	***45.7***	***4.4***	***139.2***	***430.3***	***62.0***	***293.1***	***221.7***	***41.5***	***4.1***	***126.0***	***393.2***	***58.7***	***295.8***
Tropical Regrowth Forest																												
India	0.1	0.0	0.0	0.5	**0.6**	0.2	75.8	0.3	0.0	0.0	0.5	**0.8**	0.2	95.7	0.3	0.0	0.0	0.5	**0.8**	0.3	94.1	0.3	0.0	0.0	0.5	**0.9**	0.3	95.5
Other South Asia	0.1	0.0	0.0	0.1	**0.2**	0.1	84.1	0.1	0.0	0.0	0.1	**0.2**	0.1	107.7	0.1	0.0	0.0	0.1	**0.2**	0.1	109.9	0.1	0.0	0.0	0.1	**0.2**	0.1	111.0
Southeast Asia	3.0	0.6	0.1	2.9	**6.5**	2.3	123.0	5.0	0.7	0.1	3.1	**8.9**	2.2	104.4	7.6	0.8	0.1	3.5	**12.0**	3.0	120.9	10.7	0.9	0.1	4.0	**15.7**	3.7	135.1
Africa	3.6	1.7	0.1	8.7	**14.1**	2.4	98.6	7.1	1.8	0.1	9.4	**18.4**	3.9	103.5	11.3	1.9	0.2	10.2	**23.6**	5.1	119.1	15.9	2.1	0.2	11.0	**29.2**	6.1	138.4
Mexico	0.3	0.0	0.0	0.5	**0.8**	0.1	26.8	0.4	0.0	0.0	0.7	**1.2**	0.2	36.6	0.6	0.0	0.0	0.8	**1.4**	0.2	41.8	0.5	0.0	0.0	0.8	**1.4**	0.2	41.5
Central America	0.6	0.2	0.0	1.4	**2.2**	0.3	95.0	1.4	0.2	0.0	1.5	**3.2**	0.4	135.1	2.3	0.2	0.0	1.6	**4.1**	0.5	175.7	3.1	0.3	0.0	1.7	**5.1**	0.6	212.0
South America	2.8	2.1	0.2	4.0	**9.2**	1.7	103.5	6.3	2.2	0.2	4.4	**13.1**	3.3	124.6	10.2	2.4	0.3	4.9	**17.7**	4.4	155.2	14.8	2.5	0.3	5.4	**23.0**	5.2	158.4
Subtotal	***10.5***	***4.6***	***0.4***	***18.0***	***33.6***	***3.8***	***96.4***	***20.7***	***5.0***	***0.5***	***19.7***	***45.9***	***5.6***	***105.2***	***32.4***	***5.4***	***0.6***	***21.6***	***59.9***	***7.4***	***124.8***	***45.5***	***5.9***	***0.7***	***23.5***	***75.6***	***8.8***	***139.4***
All Tropical Forest																												
India	2.2	0.0	0.1	3.8	**6.1**	1.4	95.0	3.0	0.0	0.1	3.9	**7.0**	1.4	103.2	3.0	0.0	0.1	4.0	**7.1**	1.4	102.3	3.1	0.0	0.1	4.1	**7.4**	1.6	102.2
Other South Asia	1.4	0.0	0.1	0.6	**2.0**	0.4	127.8	1.5	0.0	0.1	0.7	**2.4**	0.5	137.9	1.5	0.0	0.1	0.7	**2.3**	0.5	139.6	1.5	0.0	0.1	0.7	**2.3**	0.5	141.7
Southeast Asia	48.8	9.2	0.8	20.2	**78.9**	9.7	323.6	38.7	6.9	0.6	15.6	**61.8**	44.3	278.4	37.5	6.3	0.6	14.3	**58.7**	7.3	269.2	34.0	5.2	0.5	12.2	**51.9**	6.5	251.7
Africa	88.9	20.5	1.5	73.4	**184.3**	48.4	248.1	86.6	18.9	1.4	66.9	**173.8**	44.4	244.8	86.2	17.8	1.4	61.9	**167.4**	40.9	247.6	85.5	16.6	1.4	57.3	**160.8**	38.0	252.5
Mexico	1.9	0.2	0.1	3.1	**5.3**	0.6	75.7	1.9	0.2	0.1	3.0	**5.2**	0.4	75.7	2.1	0.2	0.1	3.0	**5.3**	0.4	79.0	2.0	0.2	0.1	2.9	**5.2**	0.5	79.0
Central America	2.3	0.5	0.0	2.4	**5.3**	0.5	155.2	3.0	0.5	0.0	2.4	**5.9**	0.5	179.6	3.6	0.5	0.0	2.3	**6.4**	0.6	206.2	4.2	0.5	0.1	2.3	**7.0**	6.1	231.6
South America	145.4	29.0	2.9	85.1	**262.3**	32.2	269.4	142.4	27.6	2.8	79.5	**252.3**	31.2	273.4	139.6	26.3	2.7	74.5	**243.1**	46.6	279.3	136.8	24.9	2.6	70.0	**234.2**	45.0	277.5
Subtotal	***291.0***	***59.3***	***5.4***	***188.6***	***544.3***	***59.0***	***253.8***	***277.0***	***54.2***	***5.1***	***171.9***	***508.3***	***54.8***	***249.1***	***273.4***	***51.1***	***5.0***	***160.8***	***490.2***	***62.5***	***251.6***	***267.2***	***47.4***	***4.8***	***149.5***	***468.8***	***59.3***	***250.5***
Global Total	**379.7**	**80.2**	**31.6**	**421.7**	**913.2**	**60.7**	**227.1**	**371.3**	**76.1**	**31.9**	**406.6**	**885.9**	**56.6**	**225.4**	**374.1**	**74.5**	**32.5**	**400.9**	**882.1**	**64.1**	**227.7**	**371.5**	**72.5**	**32.6**	**392.9**	**869.5**	**61.1**	**228.1**

Note: [1] Includes carbon stock for the reporting year on “forest land remaining forest land” and “new forest land” (afforested land).

[2] Europe (boreal) includes Norway, Sweden, and Finland.

[3] Excluding Interior Alaska and Hawaii.

[4] Europe (temperate) includes European countries (EU-25) Albania, Bosnia Herzegovina, Serbia, Switzerland, except for Norway, Sweden, and Finland.

[5] Other Europe includes Ukraine, Belarus, Georgia, Armenia, Azerbaijan, and Turkey.

[6] Other countries include Mongolia and Kazakhstan.

[7] Other South Asia includes Afghanistan, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka

[8] Southeast Asia includes Indonesia, Malaysia, Philippines, Vietnam, Cambodia, Thailand, Myanmar, Laos.

Extended Data Table 3. Estimated annual change in forest C stock (Tg C year^{-1}) by biome, country, or region for 3 decades respectively from 1990 to 2020.

	1990-1999								2000- 2009								2010- 2019							
Biome and country /region	Total living biomass	Dead wood	Litter	Soil	Harvested wood products	Net C stock change	Uncertainty of net stock change (±)	Stock change per area (MgC ha^{-1} year^{-1})	Total living biomass	Dead wood	Litter	Soil	Harvested wood products	Net C stock change	Uncertainty of net stock change	Stock change per area (MgC ha^{-1} year^{-1})	Total living biomass	Dead wood	Litter	Soil	Harvested wood products	Net C stock change	Uncertainty of net stock change	Stock change per area (MgC ha^{-1} year^{-1})
Boreal Forest[1]																								
Asian Russia	145.1	58.7	31.7	105.5	6.3	**347.3**	59.6	0.53	127.7	61.6	34.5	109.3	4.5	**337.6**	48.2	0.51	-19.8	84.5	35.8	95.7	5.9	**202.1**	22.8	0.30
European Russia	68.0	25.9	10.8	20.1	7.1	**131.9**	19.4	0.75	74.9	23.3	13.3	24.9	6.2	**142.6**	18.3	0.79	69.2	28.1	13.8	17.3	5.7	**134.1**	13.1	0.73
Canada	-6.4	-16.7	10.0	2.6	10.9	**0.4**	0.1	0.00	-55.1	11.1	8.8	2.7	12.2	**-20.2**	5.5	-0.09	-29.3	-8.2	-17.9	1.8	5.9	**-47.8**	12.9	-0.21
Alaska Interior	4.7	0.1	-0.2	0.0	0.0	**4.5**	1.4	0.19	3.8	-0.3	-2.8	0.0	0.0	**0.7**	0.2	0.03	3.7	-0.2	-1.2	-1.3	0.0	**1.1**	0.3	0.04
European boreal[2]	14.7	1.5	2.2	-0.6	5.5	**23.3**	7.0	0.37	13.1	1.3	2.0	1.9	6.8	**25.1**	8.0	0.40	20.4	2.0	2.0	3.0	7.4	**34.8**	10.4	0.40
Subtotal	***226.1***	***69.5***	***54.5***	***127.6***	***29.8***	***507.5***	***63.1***	***0.44***	***164.5***	***97.1***	***55.8***	***138.8***	***29.8***	***485.8***	***52.5***	***0.42***	***44.1***	***106.2***	***32.5***	***116.5***	***24.9***	***324.3***	***41.1***	***0.28***
Temperate Forest[1]																								
United States[3]	143.4	26.7	1.7	1.1	32.3	**205.1**	22.2	0.80	134.5	26.9	0.5	-2.1	24.3	**184.0**	19.9	0.71	132.3	27.5	-0.8	-0.4	23.3	**181.9**	19.6	0.71
European temperate[4]	89.5	20.9	2.0	5.3	8.2	**125.9**	18.7	1.17	101.3	3.9	2.1	7.9	17.0	**132.3**	20.9	1.17	79.8	3.0	3.0	11.9	18.9	**116.6**	18.1	0.99
Other Europe[5]	41.3	0.2	3.0	21.1	2.1	**67.8**	14.8	1.64	35.5	0.2	1.5	11.3	2.1	**50.5**	10.5	1.18	30.6	0.1	2.3	28.9	3.3	**65.3**	16.4	1.48
China	46.0	2.6	0.6	10.9	18.6	**78.7**	12.7	0.56	121.2	6.8	6.0	12.9	17.5	**164.4**	25.8	1.07	180.2	7.4	6.1	32.6	24.2	**250.5**	38.0	1.48
Japan	27.1	0.0	0.0	-1.3	7.7	**33.5**	9.6	1.33	25.4	0.0	0.0	-0.6	7.5	**32.3**	8.8	1.29	12.7	0.0	0.0	-0.8	10.9	**22.8**	4.1	0.91
Korea	11.6	0.0	0.9	9.7	0.4	**22.5**	5.7	1.71	16.4	0.0	1.3	13.7	0.6	**32.0**	8.0	2.50	13.1	0.0	1.0	12.0	0.6	**26.8**	6.8	2.15
Australia	-15.9	-2.0	-0.1	-4.1	1.9	**-20.2**	6.8	-0.17	-12.5	-0.9	0.5	-3.4	1.9	**-14.4**	4.8	-0.12	7.4	-0.8	0.5	-5.3	1.2	**3.0**	1.0	0.02
New Zealand	6.3	1.0	0.3	4.6	1.1	**13.3**	3.2	1.38	7.9	0.7	0.2	-0.3	1.4	**9.9**	2.8	1.01	7.8	0.9	-0.1	0.3	2.2	**11.1**	2.8	1.13
Other countries[6]	-0.1	0.0	0.0	-0.2	0.05	**-0.4**	0.1	-0.02	0.11	0.0	0.0	0.2	0.06	**0.5**	0.2	0.03	1.7	0.3	0.7	3.8	0.06	**6.6**	2.0	0.38
Subtotal	***349.2***	***49.3***	***8.3***	***47.0***	***72.4***	***526.2***	***37.4***	***0.70***	***429.8***	***37.6***	***12.1***	***39.7***	***72.4***	***591.6***	***42.2***	***0.77***	***465.5***	***38.5***	***12.8***	***83.0***	***84.7***	***684.7***	***50.0***	***0.87***
Tropical Intact Forest																								
India	50.2	0.1	3.4	10.1	13.8	**77.6**	12.9	1.34	0.4	0.0	0.8	7.1	16.8	**25.2**	2.9	0.42	12.5	0.1	0.4	8.5	18.5	**40.0**	4.2	0.65
Other South Asia[7]	7.8	0.4	-0.1	6.0	4.8	**18.9**	5.5	1.30	-3.5	-0.2	-0.1	0.1	4.3	**0.6**	1.4	0.04	-1.2	0.0	0.0	0.0	4.4	**3.3**	1.2	0.21
Southeast Asia	82.2	10.4	1.7	4.0	19.6	**118.0**	45.0	0.72	70.9	8.9	1.5	2.7	13.8	**97.8**	36.5	0.77	61.1	7.8	1.3	3.8	14.9	**88.8**	34.1	0.85
Africa	379.2	48.2	8.0	13.9	27.2	**476.4**	138.7	0.84	355.3	45.1	7.5	10.7	32.9	**451.4**	94.3	0.89	298.1	37.9	6.3	16.7	38.6	**397.5**	133.3	0.88
Mexico	17.9	2.3	0.4	0.9	1.1	**22.5**	6.2	0.60	16.1	2.1	0.3	0.8	2.3	**21.7**	6.0	0.64	15.5	2.0	0.3	0.7	2.3	**20.9**	5.7	0.65
Central America	6.7	0.6	0.1	0.2	2.3	**9.9**	2.7	0.99	3.7	0.5	0.1	0.2	2.6	**7.0**	1.9	0.83	2.3	0.3	0.0	0.2	2.7	**5.6**	1.5	0.82
South America	451.1	57.3	9.5	20.9	21.7	**560.5**	138.4	0.66	341.4	43.5	7.2	16.5	18.6	**427.3**	160.0	0.54	241.7	30.7	5.1	26.0	20.8	**324.3**	190.5	0.45
Subtotal	***995.2***	***119.3***	***23.0***	***56.0***	***90.4***	***1283.8***	***201.6***	***0.75***	***784.3***	***99.9***	***17.3***	***38.0***	***91.5***	***1030.9***	***189.4***	***0.67***	***630.0***	***78.7***	***13.5***	***56.2***	***102.2***	***880.6***	***235.1***	***0.63***
Tropical Regrowth Forest																								
India	16.4	0.0	0.5	-0.1	0.0	**16.8**	4.9	2.09	1.3	0.0	0.2	3.8	0.0	**5.3**	1.9	0.63	3.4	0.0	0.1	1.6	0.0	**5.1**	1.3	0.57
Other South Asia[7]	3.9	0.1	0.0	1.3	0.0	**5.2**	2.1	2.59	0.4	0.0	0.0	0.5	0.0	**1.0**	0.3	0.46	0.1	0.0	0.0	0.8	0.0	**0.9**	0.4	0.45
Southeast Asia	198.1	7.1	1.4	29.1	0.0	**235.6**	105.6	3.41	263.5	9.4	1.9	38.8	0.0	**313.6**	125.4	3.39	306.1	10.9	2.2	45.3	0.0	**364.5**	151.4	3.38
Africa	356.1	13.2	2.6	67.4	0.0	**439.3**	168.8	2.74	418.0	15.5	3.1	79.1	0.0	**515.6**	153.6	2.74	454.7	16.8	3.4	86.0	0.0	**560.9**	194.5	2.74
Mexico	67.0	4.9	0.1	10.2	0.0	**82.2**	22.6	2.56	60.4	4.5	0.1	9.2	0.0	**74.2**	20.4	2.18	57.9	4.3	0.1	8.8	0.0	**71.1**	19.6	2.09
Central America	82.6	2.9	0.6	9.8	0.0	**95.9**	26.4	4.11	83.6	2.9	0.6	9.9	0.0	**96.9**	26.7	4.13	85.4	3.0	0.6	10.0	0.0	**99.0**	27.2	4.15
South America	343.4	12.0	2.4	40.7	0.0	**398.4**	163.3	4.11	390.2	13.6	2.7	46.1	0.0	**452.6**	212.4	4.13	464.4	16.1	3.2	54.5	0.0	**538.3**	220.9	4.15
Subtotal	***1067.4***	***40.1***	***7.5***	***158.3***	***0.0***	***1273.4***	***259.9***	***3.25***	***1217.4***	***45.9***	***8.6***	***187.3***	***0.0***	***1459.1***	***292.5***	***3.18***	***1372.1***	***51.2***	***9.5***	***207.0***	***0.0***	***1639.8***	***332.7***	***3.21***
All Tropical Forest																								
India	66.6	0.1	3.9	10.0	13.8	**94.4**	13.8	1.44	1.7	0.1	1.0	10.9	16.8	**30.5**	3.4	0.44	15.8	0.1	0.5	10.2	18.5	**45.1**	4.0	0.64
Other South Asia[7]	11.7	0.5	-0.1	7.3	4.8	**24.2**	5.8	1.45	-3.0	-0.2	-0.1	0.5	4.3	**1.5**	1.4	0.09	-1.2	0.0	0.0	0.8	4.4	**4.0**	1.2	0.24
Southeast Asia	280.3	17.5	3.1	33.1	19.6	**353.6**	114.8	1.52	334.4	18.3	3.4	41.5	13.8	**411.4**	130.6	1.87	367.3	18.7	3.5	49.0	14.9	**453.4**	155.2	2.14
Africa	735.3	61.3	10.6	81.2	27.2	**915.7**	218.5	1.26	773.2	60.6	10.6	89.7	32.9	**967.0**	180.3	1.40	752.8	54.7	9.6	102.7	38.6	**958.4**	235.8	1.46
Mexico	84.9	7.2	0.5	11.1	1.1	**104.7**	23.4	1.51	76.5	6.5	0.4	10.0	2.3	**95.8**	21.2	1.42	73.4	6.3	0.4	9.6	2.3	**92.0**	14.6	1.39
Central America	89.3	3.4	0.7	10.0	2.3	**105.7**	26.5	3.18	87.2	3.4	0.7	10.0	2.6	**103.9**	26.7	3.26	87.7	3.3	0.6	10.3	2.7	**104.6**	27.3	3.40
South America	794.5	69.2	11.9	61.6	21.7	**958.9**	214.0	1.01	731.6	57.1	9.9	62.6	18.6	**879.9**	265.9	0.98	706.1	46.8	8.3	80.7	20.8	**862.8**	291.7	1.01
Subtotal	***2062.6***	***159.4***	***30.5***	***214.3***	***90.4***	***2557.2***	***328.9***	***1.22***	***2001.7***	***145.8***	***25.9***	***225.2***	***91.5***	***2490.0***	***348.5***	***1.25***	***2002.1***	***129.9***	***23.0***	***263.2***	***102.2***	***2520.5***	***407.4***	***1.32***
Global Total	**2637.9**	**278.3**	**93.3**	**389.0**	**192.6**	**3591.0**	***337.0***	**0.90**	**2596.0**	**280.4**	**93.7**	**403.7**	**193.7**	**3567.4**	***354.9***	***0.91***	**2511.7**	**274.7**	**68.3**	**462.8**	**211.9**	**3529.8**	***412.5***	**0.92**

Note: [1] Includes carbon stock for the reporting year on "forest land remaining forest land" and "new forest land" (afforested land).

[2] Europe (boreal) includes Norway, Sweden, and Finland.

[3] Excluding Interior Alaska and Hawaii.

[4] Europe (temperate) includes European countries (EU-28), Albania, Bosnia Herzegovina, Serbia, Switzerland, except for Norway, Sweden, and Finland.

[5] Other Europe includes Ukraine, Belarus, Georgia, Armenia, Azerbaijan, and Turkey.

[6] Other countries include Mongolia and Kazakhstan.

[7] Other South Asia includes Afghanistan, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka.

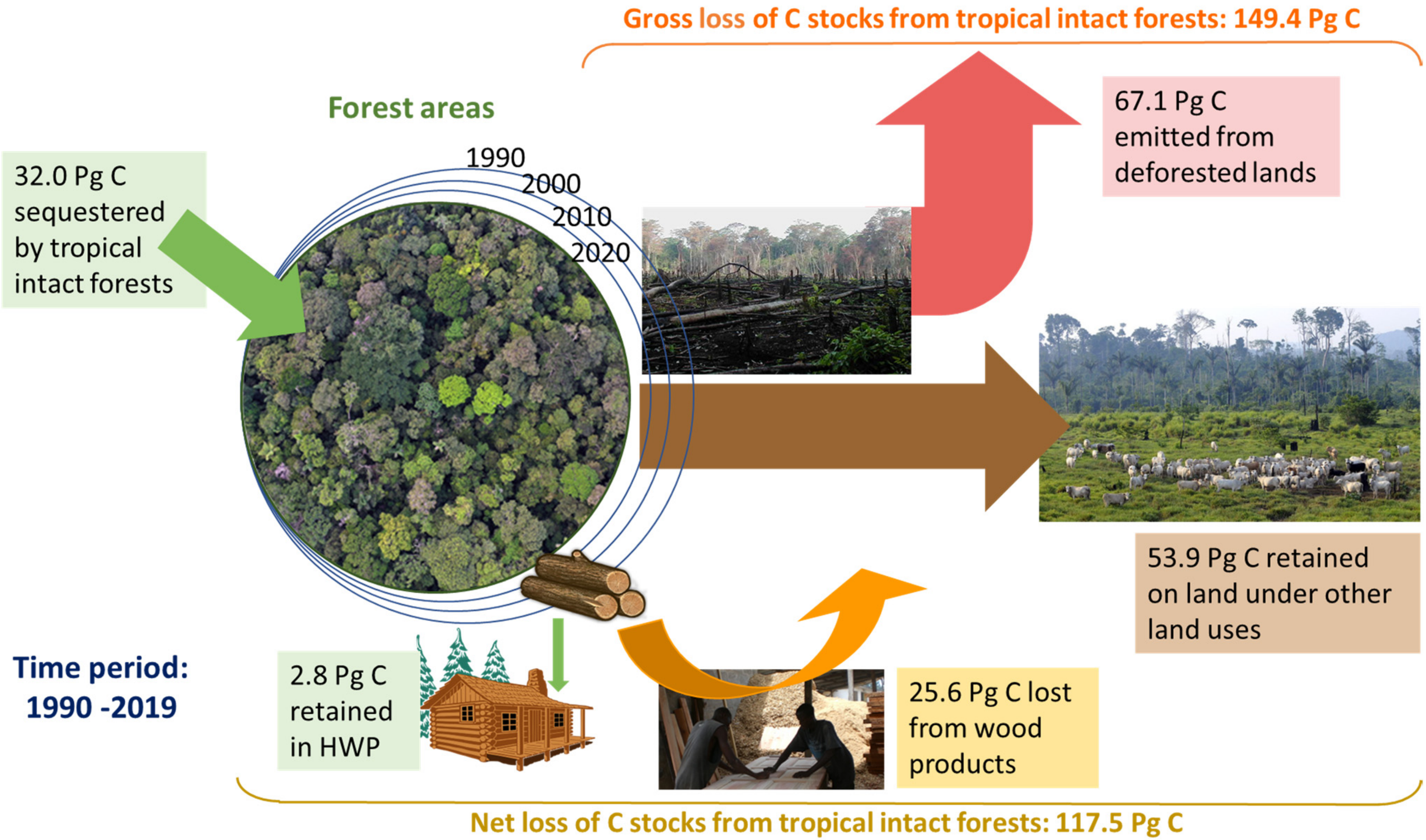
[8] Southeast Asia includes Indonesia, Malaysia, Philippines, Vietnam, Cambodia, Thailand, Myanmar, Laos.

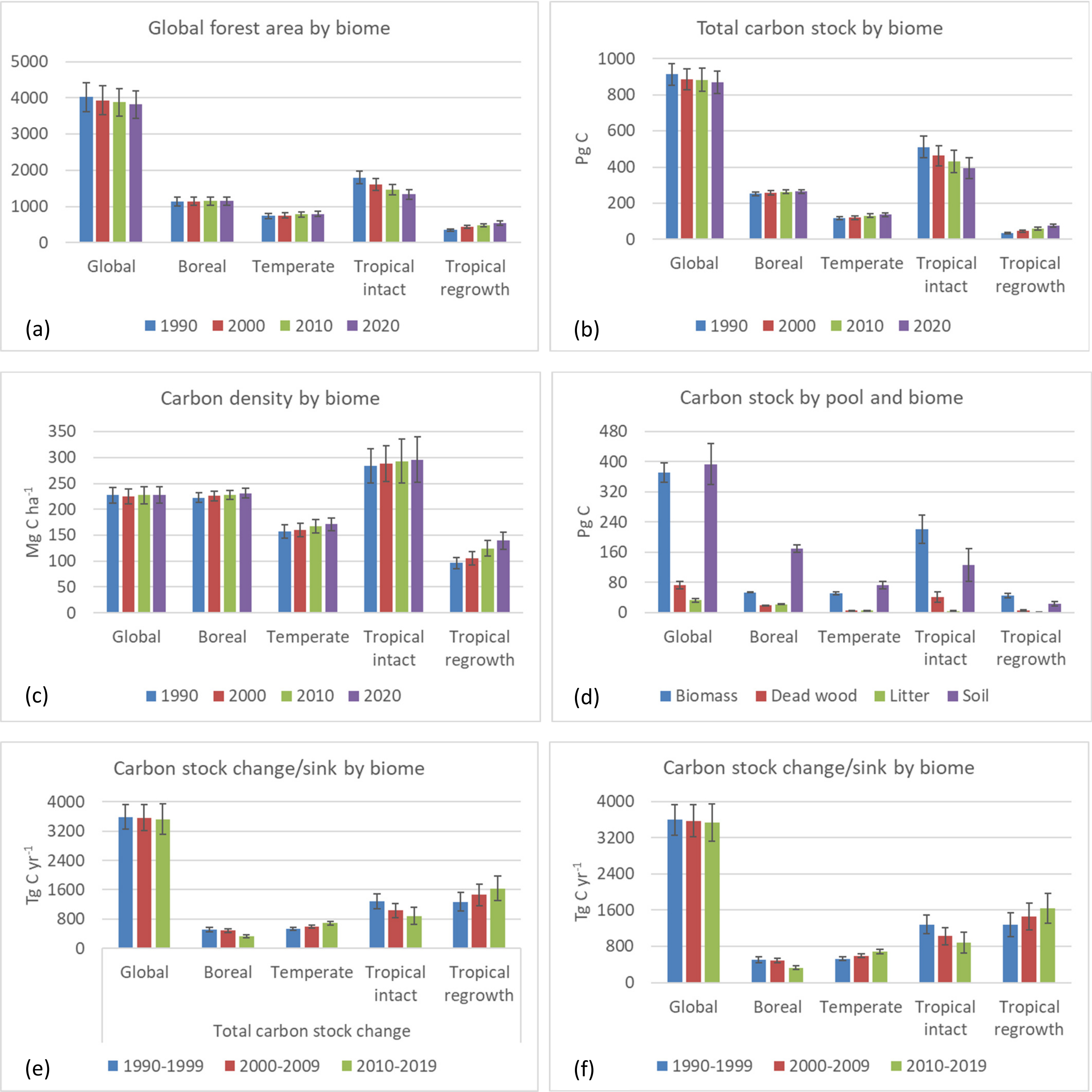
Extended Data Table 4. Alternative accounting of the Global Carbon Budget (Pg C year^{-1})

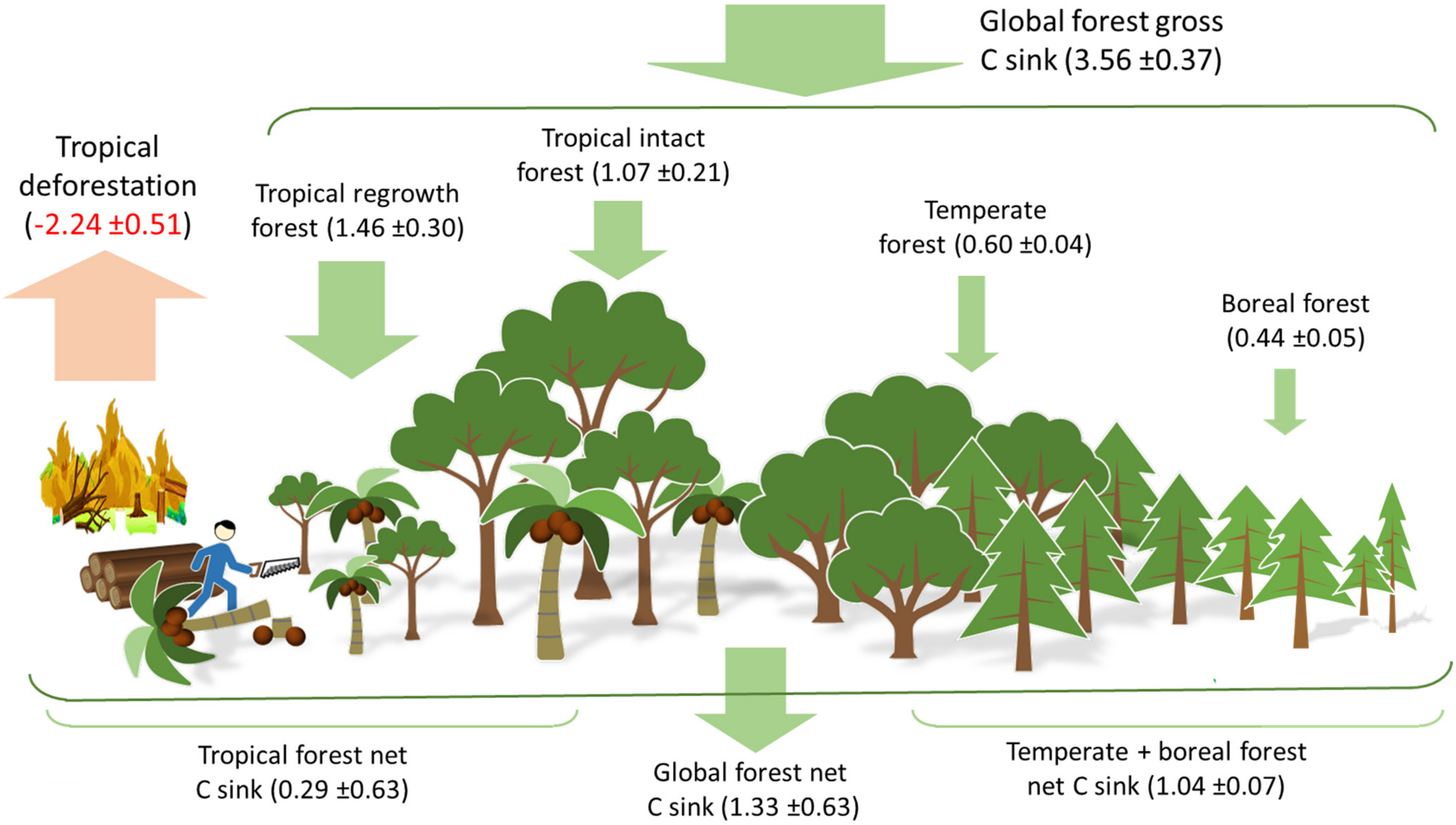
Global C fluxes and budget	1990-1999	2000-2009	2010-2019[1]	1990-2019 (Mean)	1990-2019 (Total, PgC)
Sources (C emissions):					
Fossil fuel emission (E_{FOS})[2]	-6.3 ± 0.3	-7.7 ± 0.4	-9.5 ± 0.5	-7.8 ± 0.4	-235 ± 2.2
Land-use change (LUC) ***gross*** emission (E_{GLUC})[3]	-3.6 ± 0.6	-3.7 ± 0.6	- 3.8 ± 0.6	-3.7 ± 0.6	-111 ± 3.3
Total ***gross*** C emission (E_{FOS} + E_{GLUC})[4]	-9.9 ± 0.7	-11.4 ± 0.7	- 13.3 ± 0.8	-11.5 ± 0.7	-346 ± 4.0
Sinks (C sequestration):					
Atmosphere (G_{ATM})[5]	3.1 ± 0.02	4.0 ± 0.02	5.1 ± 0.02	4.1 ± 0.02	122 ± 0.11
Ocean (S_{OCEAN})[6]	2.0 ± 0.4	2.2 ± 0.4	2.8 ± 0.4	2.3 ± 0.4	70 ± 2.2
Global land ***gross*** C sink (S_{GLAND})[7]	4.8 ± 0.8	5.2 ± 0.8	5.4 ± 0.9	5.1 ± 0.8	154 ± 4.6
Land C fluxes:					
Global C sink in established forests[8]	2.3 ± 0.2	2.1 ± 0.2	1.9 ± 0.2	2.1 ± 0.2	63.2 ± 1.2
Global ***gross*** C sink in all Earth's forests[9]	3.6 ± 0.3	3.6 ± 0.4	3.5 ± 0.4	3.6 ± 0.4	106.9 ± 2.0
Global non-forest land ***gross*** C sink (S_{GLAND} - S_{GFOR})[10]	1.2 ± 0.9	1.6 ± 0.9	1.9 ± 1.0	1.6 ± 0.9	47.1 ± 5.1
Tropical deforestation ***gross*** emission (E_{DFOR})[11]	-2.7 ± 0.5	-1.9 ± 0.4	-2.1 ± 0.6	-2.2 ± 0.5	-67.1 ± 2.8
Global non-forest LUC ***gross*** emission (E_{GLUC} - E_{DFOR})[12]	-0.9 ± 0.8	-1.8 ± 0.7	-1.7 ± 0.8	-1.5 ± 0.8	-43.9 ± 4.2
Global land ***net*** sink (S_{NLAND})[13]	1.2 ± 1.0	1.5 ± 1.0	1.6 ± 1.1	1.4 ± 1.0	43 ± 5.7
Global forest ***net*** sink (S_{NFOR})[14]	0.9 ± 0.6	1.7 ± 0.6	1.4 ± 0.7	1.3 ± 0.6	39.8 ± 3.5

Notes and definitions of C fluxes in the table and the global carbon budget, red and (-) values are C sources, while black and (+) values are C sinks:

1. Estimates are derived from the Global Carbon Budget (GCB) Table 6 of Friedlingstein et al.[2], in which the last decade is presented as 2011-2020, while in this study 2010-2019.
2. **Fossil fuel emissions** (E_{FOS}) are derived from Table 6 of Friedlingstein et al.[2].
3. **Land-use change (LUC) *gross* emissions** (E_{GLUC}) are derived from Table 5 of Friedlingstein et al.[2], which are all *LUC* gross emissions including tropical deforestation gross emissions.
4. **Total *gross* C emissions** are the result of E_{FOS}+ E_{GLUC}
5. **Atmosphere** C growth (G_{ATM}) is derived from Table 6 of Friedlingstein et al.[2], which is the increase of atmospheric carbon (in the CO_2 form).
6. **Ocean** C sequestration (S_{OCEAN}) was derived from Table 6 of Friedlingstein et al.[2], which is the carbon absorbed by oceans.
7. **Global land *gross* C sink** (S_{GLAND}) is the result of **Total *gross* C emissions** minus the C growth in the Atmosphere (G_{ATM}) and carbon sequestration by Ocean (S_{OCEAN}), so often viewed as the residual sink.
8. **Global C sink in established forests** include boreal, temperate and tropical intact forests (excluding tropical regrowth forest, which means excluding LUC).
9. **Global *gross* C sink in all Earth's forests** (S_{GFOR}) is the estimate from this study (Table 1).
10. **Global non-forest land *gross* C sink** is the result of S_{GLAND} - S_{GFOR}
11. **Tropical deforestation *gross* emission** (E_{DFOR}) is the estimate from this study (Table 1).
12. **Global non-forest *gross* emission** is the result of E_{GLUC} - E_{DFOR}.
13. **Global land *net* sink** (S_{NLAND}) is the balance between S_{GLAND} and E_{GLUC}.
14. **Global forest *net* sink** (S_{NFOR}) is the balance between S_{GFOR} and E_{DFOR} and the estimate from this study (Table 1).


Gross loss of C stocks from tropical intact forests: 149.4 Pg C
Forest areas
1990
2000
2010
2020
32.0 Pg C sequestered by tropical intact forests
67.1 Pg C emitted from deforested lands
53.9 Pg C retained on land under other land uses
Time period: 1990 -2019
2.8 Pg C retained in HWP
25.6 Pg C lost from wood products
Net loss of C stocks from tropical intact forests: 117.5 Pg C


Global forest area by biome
5000
4000
3000
2000
1000
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
(a)
1990
2000
2010
2020
Total carbon stock by biome
Pg C
1000
800
600
400
200
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
(b)
1990
2000
2010
2020
Carbon density by biome
Mg C ha^{-1}
350
300
250
200
150
100
50
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
(c)
1990
2000
2010
2020
Carbon stock by pool and biome
Pg C
480
400
320
240
160
80
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
(d)
Biomass
Dead wood
Litter
Soil
Carbon stock change/sink by biome
Tg C yr^{-1}
4000
3200
2400
1600
800
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
Total carbon stock change
(e)
1990-1999
2000-2009
2010-2019
Carbon stock change/sink by biome
Tg C yr^{-1}
4000
3200
2400
1600
800
0
Global
Boreal
Temperate
Tropical intact
Tropical regrowth
(f)
1990-1999
2000-2009
2010-2019


Global forest gross
C sink (3.56 ±0.37)
Tropical
deforestation
(-2.24 ±0.51)
Tropical regrowth
forest (1.46 ±0.30)
Tropical intact
forest (1.07 ±0.21)
Temperate
forest (0.60 ±0.04)
Boreal forest
(0.44 ±0.05)
Tropical forest net
C sink (0.29 ±0.63)
Global forest net
C sink (1.33 ±0.63)
Temperate + boreal forest
net C sink (1.04 ±0.07)