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A Large and Persistent Carbon Sink in the World's Forests

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The terrestrial carbon (C) sink has been large in recent decades, but its size and location remain uncertain. Using forest inventory data and long-term ecosystem C studies, we estimated a total forest sink of 2.4 ± 0.4 Pg C yr^{-1} globally for 1990-2007. We also estimated a source of 1.3 ± 0.7 Pg C yr^{-1} from tropical land-use change, consisting of a gross tropical deforestation emission of 2.9 ± 0.5 Pg C yr^{-1} partially compensated by a C sink in tropical forest regrowth of 1.6 ± 0.5 Pg C yr^{-1}. Together, the fluxes comprise a net global forest sink of 1.1 ± 0.8 Pg C yr^{-1}, with tropical estimates having the largest uncertainties. This forest sink is equivalent in magnitude to the terrestrial sink deduced from fossil fuel emissions and constraints of ocean and atmospheric sinks.

Forests have an important role in the global C cycle and are valued globally for the services provided to society. International negotiations to limit greenhouse gases require understanding of the current and potential future role of forest C emissions and sequestration in both managed and unmanaged forests. Estimates by the Intergovernmental Panel on Climate Change show that the net uptake by terrestrial ecosystems ranges from less than 1.0 to as much as 2.6 PgC yr^{-1} for the 1990s (*1*). More recent global C analyses have estimated a terrestrial C sink in the range of 2.0 to 3.4 PgC yr^{-1} based on atmospheric CO_2 observations and inverse modeling, and land observations (*2–4*). Because of this uncertainty and the possible change in magnitude over time, constraining these estimates is critically important to support future climate mitigation actions.

Here, we present bottom-up estimates of C stocks and fluxes for the world's forests based on recent inventory data and long-term field observations coupled to statistical or process models (table S1). We advanced our analyses by including comprehensive C pools of the forest sector (dead wood, harvested wood products, living biomass, litter and soil) and report past trends and changes in C stocks across countries, regions and continents, representing boreal, temperate, and tropical forests (*5*, *6*). To gain full knowledge of the tropical C balance, we subdivided tropical forests into intact and regrowth forests (Table 1). The latter is an overlooked category and its C uptake usually not reported, but implicit in the tropical land-use change emission estimates. While deforestation, reforestation, afforestation and the carbon outcomes of various management practices are included in the assessments of boreal and temperate forest C sink estimates, we estimated separately three major fluxes in the tropics: C uptake by intact forests, losses from deforestation, and C uptake of forest regrowth following anthropogenic disturbances. The area of global forests used as a basis for estimating C stocks and fluxes is 3.9 billion ha, representing 95% of the world's forests (*7*) (table S2).

Global forest C stocks and changes. The current C stock in the world's forests is estimated to be 861 ± 66 PgC, with 383 ± 30 PgC (44%) in soil (to 1m depth), 363 ± 28 PgC (42%) in live biomass (above- and below-ground), 73 ± 6 PgC (8%) in deadwood, and 43 ± 3 PgC (5%) in litter (table S3). Geographically, 471 ± 93 PgC (55%) is stored in tropical forests, with 272 ± 23 PgC (32%) in boreal and 119 ± 6 PgC (13%) in temperate forests. The C stock density in tropical and boreal forests is comparable (242 versus 239 Mg C ha^{-1}), while the density in temperate forests is about 60% of the other two biomes (155 Mg C ha^{-1}). Although tropical and boreal forests store the most carbon, there is a fundamental difference in their carbon structures: tropical forests have 56% of carbon stored in biomass and 32% in soil, while boreal forests have only 20% in biomass and 60% in soil.

The average annual change in the C stock of established forests (Table 1) indicates a large uptake of 2.5 ± 0.4 PgC yr^{-1} for 1990-1999 and a similar uptake of 2.3 ± 0.5 PgC yr^{-1} for 2000-2007. Adding to those the C uptakes in tropical regrowth forests indicates a persistent global gross forest C sink of 4.0 ± 0.7 PgC yr^{-1} over the two periods (Tables 1 and 2). Despite the consistency of the global C sink since 1990, our analysis revealed important regional and temporal differences in sink sizes. The C sink in temperate forests increased by 17% in 2000-2007 compared to 1990-1999, in contrast to C uptake in intact tropical forests that decreased by 23% (but non-significantly). Boreal forests, on average, showed little difference between the two time periods (Fig. 1). Subtracting C emission losses from tropical deforestation and degradation, the global net forest C sink was 1.0 ± 0.8 and 1.2 ± 0.9 PgC yr^{-1} for 1990-1999 and 2000-2007 (Table 1).

Forest carbon sinks by regions, biomes, and pools. Boreal forests (1135 Mha) had a consistent average sink of 0.5 ± 0.1 PgC yr^{-1} for two decades (Table 2, 20 and 22% of the global C sink in established forests). However, the overall stability of the boreal forest C sink is the net result of contrasting carbon dynamics in different boreal countries and regions associated with natural disturbances and forest management. Asian Russia had the largest boreal sink, but that sink showed no overall increase even with increased emissions from wildfire disturbances (*8*). In contrast, there was a significant sink increase of 35% in European Russia (Fig. 1) attributed to several factors: increased areas of forests after agricultural abandonment, reduced harvesting, and changes of forest age structure to more productive stages, particularly for the deciduous forests (*8*). In contrast to the large increase of biomass sinks in European Russia and northern Europe, the biomass C sink in Canadian managed forests was reduced by half between the two periods, mostly due to the biomass loss from intensified wildfires and insect outbreaks (*9*, *10*). A net loss of soil C in northern Europe was attributed to the draining of water-logged soils (*11*). Overall, the relatively stable boreal C sink is the sum of a net reduction in Canadian biomass sink offset by increased biomass sink in all other boreal regions, and a balance between decreased litter and soil C sinks in northern Eurasia and a region-wide increase in the accumulation of dead wood (Table 2).

Temperate forests (767 Mha) contributed 0.7 ± 0.1 and 0.8 ± 0.1 PgC yr^{-1} (27% and 34%) to the global C sink in established forests for two decades (Table 2). The primary reasons for the increased C sink in temperate forests are the increasing density of biomass and a substantial increase in forest area (*12*, *13*). The U.S. forest C sink increased by 33% from the 1990s to 2000s, caused by increasing forest area, growth of existing immature forests that are still recovering from historical agriculture, grazing, harvesting (*12*, *14*), and environmental factors such as CO_2 fertilization and N deposition (*15*). However, forests in the western United States have shown significantly increased mortality in the past few decades, related to drought stress, and increased mortality from insects and fires (*16*, *17*). The European temperate forest sink was stable between 1990-1999 and 2000-2007. There was a large C sink in soil due to expansion of forests in the 1990s, but this trend slowed in the 2000s (*7*, *18*). However, the increased C sink in biomass during the second period (+17%) helped to maintain the stability of the total C sink. China's forest C sink increased by 34% between 1990-1999 and 2000-2007, with the biomass sink almost doubling (Table 2). This was caused primarily by increasing areas of newly planted forests, the consequence of an intensive national afforestation/ reforestation program in the last few decades (table S2) (*19*).

Tropical intact forests (1392 Mha) represent about 70% of the total tropical forest area (1949 Mha) that accounts for the largest area of global forest biomes (~50%). We used two networks of permanent monitoring sites spanning intact tropical forest across Africa (*20*) and South America (*21*), and assumed that forest C stocks of SE Asia (9% of total intact tropical forest area) are changing at the mean rate of Africa and South America, as we lack sufficient data in S.E. Asia to make robust estimates. These networks are large enough to capture the disturbance-recovery dynamics of intact forests (*6*, *20*, *22*). We estimate a sink of 1.3 ± 0.3 and 1.0 ± 0.5 PgC yr^{-1} for 1990-1999 and 2000-2007, respectively (Table 2). An average C sink of 1.2 ± 0.4 PgC yr^{-1} for 1990-2007 is approximately half of the total global C sink in established forests (2.4 ± 0.4 PgC yr^{-1}) (Table 1). When only the biomass sink is considered, about two-thirds of the global biomass C sink in established forests is from tropical intact forests (1.0 versus 1.5 PgC yr^{-1}). The sink reduction in the period 2000-2007 was caused by deforestation reducing intact forest area (8%), and a severe Amazon drought in 2005 (*21*) which appeared strong enough to affect the tropics-wide decadal C sink estimate (15%). Except for the Amazon drought, the recent excess of biomass C gain (growth) over loss (death) in tropical intact forests appears to result from progressively enhanced productivity (*20*, *21*, *23*). Increased dead biomass production should lead to enhanced soil C sequestration, but we lack data about changes in soil C stocks for tropical intact forests, so that the C sink for tropical intact forests may be underestimated.

Tropical land-use changes have caused net C releases in tropical regions by clearing forests for agriculture, pasture, and timber (*24*), second in magnitude to fossil fuel emissions (Table 3). Tropical land-use change emission was a net balance of C fluxes consisting of a gross tropical deforestation emission partially compensated by a C sink in tropical forest regrowth. It declined from 1.5 ± 0.7 PgC yr^{-1} in 1990s to 1.1 ± 0.7 PgC yr^{-1} for 2000-2007 (Table 1) due to reduced rates of deforestation and increased forest regrowth (*25*). The tropical land-use change emission was approximately equal to the total global land-use emission (Tables 1 and 3) because effects of land-use changes on C were roughly balanced in extratropics (*7*, *24*, *25*).

Tropical deforestation. produced significant gross C emissions of 3.0 ± 0.5 and 2.8 ± 0.5 PgC yr^{-1} respectively for 1990-1999 and 2000-2007, around 40% of the global fossil fuel emissions. However, these large emission numbers are usually neglected because more than a half was offset by large C uptake in tropical regrowth forests recovering from the deforestation, logging or abandoned agriculture. Tropical regrowth forests (557 Mha), represent about 30% of the total tropical forest area. The C uptake by tropical regrowth forests is usually implicitly included in estimated *net* emissions of tropical land-use changes rather than estimated independently as a sink (*24*).

We estimated that the C sink by tropical regrowth forests was 1.6 ± 0.5 and 1.7 ± 0.5 PgC yr^{-1} respectively for 1990-1999 and 2000-2007. Our results indicate that tropical regrowth forests were stronger C sinks than the intact forests due to rapid biomass accumulation under succession, but these estimates are poorly constrained because of sparse data (table S4) (*6*). Although distinguishing a C sink in tropical regrowth forests does not affect the estimated net emissions from tropical land-use changes, an explicit estimate of this component facilitates evaluating the complete C sink capacity of all tropical and global forests.

When all tropical forests, both intact and regrowth, are combined, the tropical sinks sum to 2.9 ± 0.6 and 2.7 ± 0.7 PgC yr^{-1} over the two periods, respectively (Table 1), and on average account for about 70% of the gross C sink in the world forests(~4.0 PgC yr^{-1}). However, with equally significant gross emissions from tropical deforestation (Table 1), tropical forests were nearly carbon neutral. In sum, the tropics have the world's largest forest area, the most intense contemporary land-use change, and the highest C uptake, but also the greatest uncertainty, showing that investment in better understanding carbon cycling in the tropics should be a high priority in the future.

Deadwood, litter, soil, and harvested wood products altogether accounted for 35% of the global sink and for 60% of the global forest C stock, showing the importance of including these components (Table 2 and table S3). Compared with biomass, estimates of these terrestrial carbon pools are generally less certain because of insufficient data. For deadwood, there was a significant sink increase in boreal forests over the last decade, caused by the recent increase in natural disturbances in Siberia and Canada. Increased deadwood carbon thus makes a major (27%) but possibly transient contribution to the total C sink in the boreal zone. Changes in litter C accounted for a relatively small and stable portion of the global forest C sink. However, litter C accumulation contributed 20% of the total C sink in boreal forests and, like deadwood, was vulnerable to wildfire disturbances. Changes in soil C stocks accounted for more than 10% of the total sink in the world's forests, largely driven by land-use change. We may underestimate global soil C stocks and fluxes because the standard 1-m soil depth excludes some deep organic soils in boreal and tropical peat forests (*27*–*29*). We estimated the net C change in harvested wood products (HWP), including wood in use and disposed in landfills, as described in the IPCC (*30*) guidelines, attributing changes in stock to the region where the wood was harvested. Carbon sequestration in HWP accounted for ~8% of the total sink in established forests. This sink remained stable for temperate and tropical regions, but declined dramatically in boreal regions because of reduced harvest in Russia in the last decade.

Data gaps, uncertainty, and suggested improvements in global forest monitoring. We estimated uncertainties based on a combination of quantitative methods and expert opinion (*6*). There are critical data gaps that affected both the results presented here and our ability to report and verify changes in forest C stocks in the future. Data are substantially lacking for areas of the boreal forest in North America including Alaska (51 Mha) and Canadian unmanaged forests (118 Mha) (table S5). The forests in these regions could be a small C source or sink, based on the estimate of Canadian managed forests (*9*) and modeling studies in Alaska (*31*). There is also a lack of measurement data of soil C flux in tropical intact forests, which may cause uncertainty of 10-20% of the estimated total C sink in these forest areas. In addition, there is a large uncertainty associated with the estimate of C stocks and fluxes in tropical Asia due to the absence of long-term field measurements and a notable lack of data about regrowth rates of tropical forests worldwide.

Prioritized recommendations for improvements in regional forest inventories to assess C density, uptake, and emissions for global-scale aggregation include: (i) land monitoring should be greatly expanded in the tropics and in un-sampled regions of northern boreal forests; (ii) a globally consistent approach to remote sensing for land-cover change and forest area estimation is required to combine the strengths of two observation systems- solid ground truth of forest C densities and reliable forest areas from remote sensing used in scaling inventory data; (iii) improved methods and greater sampling intensity are needed to estimate non-living C pools, including soil, litter, and dead wood; and (iv) better data are required in most regions for estimating lateral C transfers in harvested wood products and rivers.

Forest carbon in the global context. The new C sink estimates from world's forests can contribute to the much needed detection and attribution that is required in the context of the global carbon budget (*2*, *4*, *25*). Our results suggest that, within the limits of reported uncertainty, the entire terrestrial C sink is accounted for by C uptake of global established forests (Table 3), since the balanced global budget yields near-zero residuals with ±1.0 PgC yr^{-1} uncertainty for both 1990-1999 and 2000-2007 (Table 3). Consequently, our results imply that non-forest ecosystems are collectively neither a major (>1 Pg) C sink or source over the two time periods we monitored. Because the tropical gross deforestation emission is mostly compensated by the C uptakes in both tropical intact and regrowth forests (Fig. 1 and Table 1), the net global forest C sink (1.1 ± 0.8 PgC yr^{-1}) resides mainly in the temperate and boreal forests, consistent with previous estimates (*32*, *33*). Notably, the total gross C uptake by the world's established and tropical regrowth forests is 4.0 PgC y^{-1}, equivalent to half of the fossil fuel C emissions in 2009 (*4*). Over the period studied (1990-2007), the cumulative C sink into the world's established forests was ~43 PgC, and for the established plus regrowing forests was 73 PgC; the latter equivalent to 60% of cumulative fossil emissions in the period (i.e., 126 PgC). Clearly, forests play a critical role in the Earth's terrestrial C sinks, and exert strong control on the evolution of atmospheric CO_2.

Drivers and outlook of forest carbon sink. The mechanisms affecting the current C sink in global forests are diverse and their dynamics will determine its future longevity. The C balance of boreal forests is driven by changes in harvest patterns, regrowth over abandoned farmlands, and increasing disturbance regimes. The C balance of temperate forests is primarily driven by forest management, through low harvest rates (Europe) (*34*), recovery from past harvesting and agricultural abandonment (U.S.) (*35*), and large-scale afforestation (China) (*19*). For tropical forests, deforestation and forest degradation are dominant causes of C emissions, with regrowth and an increase in biomass in intact forests being the main sinks balancing the emissions (*23*, *24*).

Changes in climate and atmospheric drivers (CO_2, N-deposition, ozone, diffuse light) impact the C balance of forests, but it is difficult to separate their impacts from other factors using ground observations. For Europe, the U.S., China and the tropics, evidence from biogeochemical process models suggests that climate change, increasing atmospheric CO_2, and N deposition are, at different levels, significant factors driving the long-term C sink (*15*, *18*, *20*, *35*). Drought in all regions, and warmer winters in boreal regions, reduce the forest sink through suppressed gross primary production, increased fires, and increased insect damage (*8*, *9*, *18*, *21*, *30*, *36*, *37*).

Our estimates suggest that currently the global established forests, which are outside the areas of tropical land-use change, alone can account for the terrestrial C sink (~2.4 PgC yr^{-1}). The tropics are the dominant terms in the exchange of CO_2 between the land and the atmosphere. A large amount of atmospheric CO_2 has been sequestrated by the natural system of forested lands (~4.0 PgC yr^{-1}), but the benefit is significantly offset by the C losses from tropical deforestation (~2.9 PgC yr^{-1}). This result highlights the potential for Reducing Emissions from Deforestation and Degradation (REDD) to lessen the risk of climate change. However, an important caveat is that adding geological carbon from fossil fuels into the contemporary carbon cycle and then relying on biospheric sequestration is not without risk, since such sequestration is reversible from climate change and human actions.

Nonetheless, C sinks in almost all forests across the world (Fig. 1) may suggest overall favorable conditions for increasing stocks in forests and wood products. Our analysis indicates that there are extensive areas of relatively young forests with potential to continue sequestering C in the future in the absence of accelerated natural disturbance, climate variability, and land use change. Because of the large C stocks in both boreal forest soils and tropical forest biomass, warming in the boreal zone and deforestation and occasional extreme drought, co-incident with fires in the tropics represent the greatest risks to the continued large C sink in the world's forests (*21*, *24*, *31*, *38*). A better understanding of the role of forests in biosphere C fluxes and mechanisms responsible for forest C changes is critical for projecting future atmospheric CO_2 growth and guiding the design and implementation of mitigation policies.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/science.1201609/DC1
Materials and Methods
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References

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Fig. 1. Carbon sinks and sources (Pg C yr^{-1}) in the world's forests. Down-direction represents sink, while up-direction represents source. Light and dark purple colors are for global established forests (boreal, temperate and intact tropical forests), dark brown and orange colors are for tropical regrowth forests from deforested lands; and yellow and yellow green colors are for tropical gross deforestation emissions.

Table 1. Global forest carbon budget (Pg C yr^{-1}) over two time periods.

Carbon sink and source in biomes[1]	1990-1999	2000-2007	1990-2007
Boreal forest	0.50 ± 0.08	0.50 ± 0.08	0.50 ± 0.08
Temperate forest	0.67 ± 0.08	0.78 ± 0.09	0.72 ± 0.08
Tropical intact forest[2]	1.33 ± 0.35	1.02 ± 0.47	1.19 ± 0.41
Total sink in global established forests[3]	2.50 ± 0.36	2.30 ± 0.49	2.41 ± 0.42
Tropical regrowth forest[4]	1.57 ± 0.50	1.72 ± 0.54	1.64 ± 0.52
Tropical gross deforestation emission[5]	–3.03 ± 0.49	–2.82 ± 0.45	–2.94 ± 0.47
Tropical land-use change emission[6]	–1.46 ± 0.70	–1.10 ± 0.70	–1.30 ± 0.70
Global *gross* forest sink[7]	4.07 ± 0.62	4.02 ± 0.73	4.05 ± 0.67
Global *net* forest sink[8]	1.04 ± 0.79	1.20 ± 0.85	1.11± 0.82

Equations of global forest C fluxes:

$$F_{Established\ Forests} = F_{Boreal\ Forests} + F_{Temperate\ Forests} + F_{Tropical\ Intact\ Forests} \quad \text{(Eq. 1)}$$

$$F_{Tropical\ Land\text{-}use\ Change} = F_{Tropical\ Gross\ Deforestation} + F_{Tropical\ Regrowth\ Forests} \quad \text{(Eq. 2)}$$

$$F_{Gross\ Forest} = F_{Established\ Forests} + F_{Tropical\ Regrowth\ Forests} \quad \text{(Eq. 3)}$$

$$F_{Net\ Forest} = F_{Established\ Forests} + F_{Tropical\ Land\text{-}use\ Change} \quad \text{(Eq. 4)}$$

Notes and definitions of the C fluxes in the table and equations (**bold** font):
[1]Sinks (black) are positive values; and sources (red) are negative values.
[2]**Tropical Intact Forests**: Tropical forests that have not been substantially affected by direct human activities, but the flux accounts for the dynamics of natural disturbance-recovery processes.
[3]Global **Established Forests**: The forest remaining forest over the study periods plus afforested land in boreal and temperate biomes, plus intact forest in the tropics (Eq. 1).
[4]**Tropical Regrowth Forests**: Tropical forests that are recovering from past deforestation and logging.
[5]**Tropical Gross Deforestation**: The total C emissions from tropical deforestation and logging, not counting uptake of C in tropical regrowth forests.
[6]**Tropical Land-use Change**: Emissions from tropical land-use change, which is a net balance of tropical gross deforestation emissions and C uptake in regrowth forests (Eq. 2). May be referenced as a tropical net deforestation emission in the literature.
[7]Global **Gross Forest** sink: The sum of total sinks in global established forests and tropical regrowth forests (Eq. 3).
[8]Global **Net Forest** sink: the net budget of global forest fluxes (Eq. 4). It can be calculated in two ways: (i) total sink in global established forests minus tropical land-use change emission; and (ii) total global gross forest sink minus tropical gross deforestation emission.

Table 2. Estimated annual change in C stock (Tg C yr^{-1}) by biomes by country or region for the time periods of 1990-1999 and 2000-2007 (1, 2, 3).

Biome and Country/Region	1990-1999 Biomass	Dead Wood	Litter	Soil	Harvested wood product	Total stock change	Uncer-tainty(±)	Stock change per area	2000-2007 Biomass	Dead Wood	Litter	Soil	Harvested wood product	Total stock change	Uncer-tainty(±)	Stock change per area
	--------(Tg C yr^{-1})--------							(Mg C ha^{-1}yr^{-1})	--------(Tg C yr^{-1})--------							(Mg C ha^{-1}yr^{-1})
Boreal (4)																
Asian Russia	61	66	63	45	19	255	64	0.39	69	97	43	42	13	264	66	0.39
European Russia	37	10	22	36	41	146	37	0.93	84	19	35	35	26	199	50	1.21
Canada	6	-24	14	6	23	26	6	0.11	-53	16	19	7	21	10	3	0.04
European boreal (5)	13	0	3	38	11	65	16	1.12	20	0	4	-10	13	27	7	0.45
Subtotal	**117**	**53**	**103**	**125**	**94**	**493**	**76**	**0.45**	**120**	**132**	**100**	**73**	**73**	**499**	**83**	**0.44**
Temperate(4)																
United States (6)	118	6	13	9	33	179	34	0.72	147	9	18	37	28	239	45	0.94
Europe	117	2	8	81	24	232	58	1.71	137	2	8	65	27	239	60	1.68
China	60	22	15	31	7	135	34	0.96	115	24	8	28	7	182	45	1.22
Japan	24	9	ND	19	2	54	13	2.28	23	5	ND	8	2	37	9	1.59
South Korea	6	2	ND	5	0	14	3	2.14	12	2	ND	4	0	18	5	2.86
Australia	17	ND	10	15	8	50	12	0.33	17	ND	10	14	10	51	13	0.34
New Zealand	1	0	0	1	5	7	2	0.91	1	0	0	1	6	9	2	1.05
Other countries	1	ND	ND	ND	0	1	1	0.07	2	0	0	0	0	3	1	0.18
Subtotal	**345**	**42**	**46**	**160**	**80**	**673**	**78**	**0.91**	**454**	**42**	**45**	**156**	**80**	**777**	**89**	**1.03**
Tropical Intact																
Asia	125	13	2	ND	5	144	38	0.88	100	10	1	ND	6	117	30	0.90
Africa	469	48	7	ND	9	532	302	0.94	425	43	6	ND	8	482	274	0.94
Americas	573	48	9	ND	22	652	166	0.77	345	45	5	ND	23	418	386	0.53
Subtotal	**1167**	**108**	**17**	**0**	**35**	**1328**	**347**	**0.84**	**870**	**98**	**13**	**0**	**36**	**1017**	**474**	**0.71**
Global Subtotal (7)	**1630**	**204**	**166**	**286**	**209**	**2494**	**363**	**0.73**	**1444**	**273**	**158**	**230**	**188**	**2294**	**489**	**0.69**
Tropical Regrowth																
Asia	498	ND	[1]	27	ND	526	263	3.52	564	ND	[1]	29	ND	593	297	3.53
Africa	169	ND	[1]	73	ND	242	121	1.48	188	ND	[1]	83	ND	271	135	1.47
Americas	694	ND	[1]	112	ND	807	403	4.67	745	ND	[1]	113	ND	858	429	4.56
Subtotal	**1361**	**0**	**0**	**213**	**0**	**1574**	**496**	**3.24**	**1497**	**0**	**0**	**226**	**0**	**1723**	**539**	**3.19**
All Tropics (8)																
Asia	623	13	2	27	5	670	266	2.14	664	10	1	29	6	711	298	2.38
Africa	638	48	7	73	9	774	325	1.06	613	43	6	83	8	753	305	1.08
Americas	1267	48	9	112	22	1458	436	1.42	1090	45	5	113	23	1276	577	1.30
Subtotal	**2529**	**108**	**17**	**213**	**35**	**2903**	**605**	**1.40**	**2367**	**98**	**13**	**226**	**36**	**2740**	**718**	**1.38**
Global Total (9)	**2991**	**204**	**166**	**498**	**209**	**4068**	**615**	**1.04**	**2941**	**273**	**158**	**456**	**188**	**4017**	**728**	**1.04**

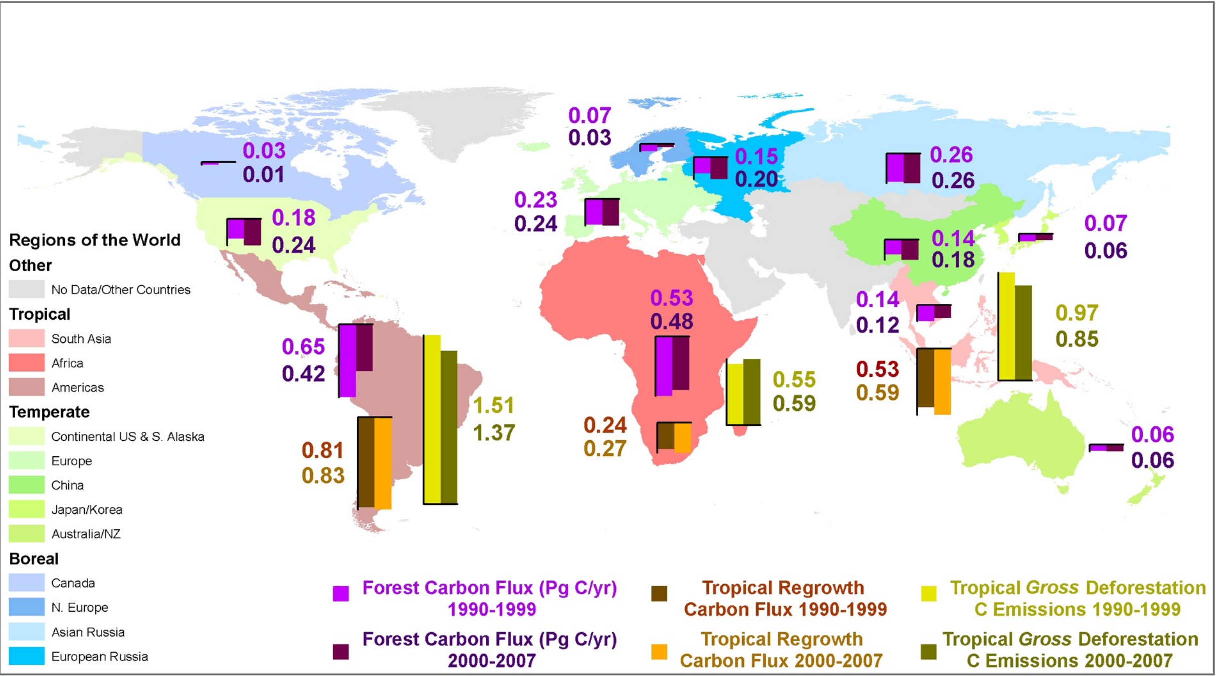
(1) Estimates include C stock changes on "forest land remaining forest land" and "new forest land" (afforested land); (2) The uncertainty calculation refers to the supporting online material; (3) ND means data not available and [1] litter is included in soils; (4) carbon outcomes of forest land-use changes (deforestation, reforestation, afforestation and management practices) are included in the estimates in boreal and temperate forests; (5) Estimates for the area that Includes Norway, Sweden, and Finland; (6) Estimates for the continental US and a small area in Southeast Alaska; (7) Estimates for global established forests; (8)

Estimates for all tropical forests including tropical intact and regrowth forests; and (9) Areas excluded from this table include Interior Alaska (51 × 106 ha in 2007), Northern Canada (118 × 106 ha in 2007), and "other wooded land" reported to FAO.

Table 3. The global carbon budget (accounting based on sources and sinks) for two time periods (PgC yr^{-1}) (1).

Sources and Sinks	**1990-1999**	**2000-2007**
Sources (emissions):		
Fossil fuel and cement (2)	6.5±0.4	7.6±0.4
Land-use change (3)	1.5±0.7	1.1±0.7
Total sources	8.0±0.8	8.7±0.8
Sinks (C uptakes):		
Atmosphere (3)	3.2±0.1	4.1±0.1
Ocean (4)	2.2±0.4	2.3±0.4
Terrestrial (Established forests) (5)	2.5±0.4	2.3±0.5
Total sinks	7.9±0.6	8.7±0.7
Global residuals (6):	0.1±1.0	0.0±1.0

(1) There are different arrangements to account for elements of the global C budget (also see table S6). Here the accounting was based on global C sources and sinks. The terrestrial sink was the residual derived from constraints of two major anthropogenic sources and the sinks in the atmosphere and oceans. We used the C sink in global established forests as a proxy for the terrestrial sink.
(2) Canadell *et al*. 2007(*2*).
(3) Friedlingstein *et al*. 2010. FRA 2010, LeQuere *et al*. 2009 (*4*, *7*, *25*). The global land-use change emission is approximately equal to the tropical land-use change emission because the net carbon balance of land-use changes in temperate and boreal regions is neutral (Houghton, 2003, 2007) (*24*, *26*).
(4) LeQuere *et al*. 2009 (*4*).
(5) Estimates of C sinks in the global established forests (that are outside the areas of tropical land-use change) from this study. Note that the carbon sink in tropical regrowth forests is excluded since it is included in the term of land-use change emission, above (also referring to Table 1).
(6) Global carbon residuals are close to zero when averaged over a decade. The positive residuals indicate either a land sink in the 210 Mha of forest not included here, on non-forest land, or systematic error in other source (over-estimate) or sink (under-estimate) terms, or both.


Regions of the World
Other
No Data/Other Countries
Tropical
South Asia
Africa
Americas
Temperate
Continental US & S. Alaska
Europe
China
Japan/Korea
Australia/NZ
Boreal
Canada
N. Europe
Asian Russia
European Russia
0.03
0.01
0.18
0.24
0.07
0.03
0.15
0.20
0.26
0.26
0.23
0.24
0.14
0.18
0.07
0.06
0.53
0.48
0.14
0.12
0.97
0.85
0.65
0.42
1.51
1.37
0.81
0.83
0.55
0.59
0.53
0.59
0.24
0.27
0.06
0.06
Forest Carbon Flux (Pg C/yr) 1990-1999
Forest Carbon Flux (Pg C/yr) 2000-2007
Tropical Regrowth Carbon Flux 1990-1999
Tropical Regrowth Carbon Flux 2000-2007
Tropical Gross Deforestation C Emissions 1990-1999
Tropical Gross Deforestation C Emissions 2000-2007