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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.

Reference and Notes

1. G. J. Nabuurs *et al.*, in *Climate Change 2007: Mitigation*, B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer, Eds. (Cambridge, 2007), pp. 542–584.
2. J. G. Canadell *et al.*, Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Nat. Acad. Sci. U.S.A.* **104**, 18866 (2007).

3. S. Khatiwala, F. Primeau, T. Hall, Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* **462**, 346 (2009).
4. C. Le Quere, M. R. Raupach, J. G. Canadell, G. Marland, Trends in the sources and sinks of carbon dioxide. *Nat. Geosci.* **2**, 831 (2009).
5. R. K. Dixon *et al.*, Carbon pools and flux of global forest ecosystems. *Science* **263**, 185 (1994).
6. Details of data sources, accounting, and estimation methods used for each country, region, and C component are provided in the supporting online material.
7. Food and Agriculture Organization, *Global Forest Resources Assessment 2010* (Food and Agriculture Organization, Rome, 2010), Forestry Paper 163.
8. A. Z. Shvidenko, D. G. Schepaschenko, S. Nilsson, Materials to perception of current productivity of forest ecosystems in Russia, in *Basic Problems of Transition to Sustainable Forest Management in Russia*, V. A. Sokolov, A. Z. Shvidenko, O. P. Vtorina, Eds. (Russian Academy of Sciences, Krasnoyarsk, 2007), pp. 5–35.
9. W. A. Kurz, G. Stinson, G. J. Rampley, C. C. Dymond, E. T. Neilson, Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proc. Nat. Acad. Sci. U.S.A.* **105**, 1551 (2008).
10. G. Stinson *et al.*, An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Glob. Change Bio.*, DOI: 10.1111/j.1365-2486.2010.02369 (2010).
11. P. E. Kauppi *et al.*, Changing stock of biomass carbon in a boreal forest over 93 years. *Forest Ecology and Management*, **259(7)**, 1239 (2010)
12. R. Birdsey, K. Pregitzer, A. Lucier, Forest carbon management in the United States, 1600-2100. *J. Env. Qual.* **35**, 1461 (2006).
13. P. E. Kauppi *et al.*, Returning forests analyzed with the forest identity. *Proc. Nat. Acad. Sci. U.S.A.* **103**, 17574 (2006).
14. Y. Pan *et al.* Age structure and disturbance legacy of North American forests. *Biogeosciences* **8**, 715 (2011).
15. Y. Pan, R. Birdsey, J. Hom, K. McCullough, Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. *For. Ecol. and Manage.* **259**, 151 (2009).
16. P. J. van Mantgem *et al.*, Widespread increase of tree mortality rates in the Western United States. *Science* **323**, 521 (2009).
17. D. D. Breshears *et al.*, Regional vegetation die-off in response to global-change-type drought. *Proc. Nat. Acad. Sci. U.S.A.* **102**, 15144 (2005).
18. P. M. Ciais *et al.*, Carbon accumulation in European forests. *Nat. Geosci.* **1**, 1 (2008).
19. J. Y. Fang, A. P. Chen, C. H. Peng, S. Q. Zhao, L. Ci, Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* **292**, 2320 (2001).
20. S. L. Lewis, G. Lopez-Gonzalez, B. Sonké, K. Affum-Baffo, T. R. Baker, Increasing carbon storage in intact African tropical forests. *Nature* **477**, 1003 (2009).
21. O. L. Phillips *et al.*, Drought sensitivity of the Amazon rainforest. *Science* **323**, 1344 (2009).
22. M. Gloor *et al.* Is the disturbance hypothesis for explaining trends in Amazonian forest biomass consistent with basin-wide data? *Glob. Change Bio.* **15**, 2418 (2009).
23. S. L. Lewis, J. Lloyd, S. Sitch, E. T. A. Mitchard, W. F. Laurance. Changing ecology of tropical forests: Evidence and drivers. *Annu. Rev. Ecol. Syst.* **40**, 529 (2009).
24. R. A. Houghton, Balancing the global carbon budget. *Annu. Rev. Earth Planet. Sci.* **35**, 313 (2007).
25. P. Friedlingstein *et al.* Update on CO_2 emissions. *Nat. Geosci.* **3**, 811 (2010)
26. C. Tarnocai *et al.* Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23**, GB2023 (2009).
27. R. A. Houghton, Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus* **55B**, 378 (2003).
28. A. Hooijer *et al.* Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **7**, 1505 (2010).
29. S. E. Page, J. O. Rieley, C. J. Banks, Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* **17(2)**, 798 (2011).
30. IPCC, *IPCC Guidelines for National Greenhouse Gas Inventories* (IGES, Japan, 2006); www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
31. A. D. McGuire *et al.* Sensitivity of the carbon cycle in the Arctic to climate change. *Ecol. Monogr.* **79(4)**, 523, 2009.
32. C. L. Goodale *et al.*, Forest carbon sinks in the northern hemisphere. *Ecol. App.* **12**, 891 (2002).
33. J. L. Sarmiento *et al.*, Trends and regional distributions of land and ocean carbon sinks. *Biogeosciences* **7**, 2351 (2010).
34. E. D. Schulze *et al.*, Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. *Nat. Geosci.* **2**, 842 (2009).
35. S. W. Pacala *et al.* Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science* **292**, 2316 (2001).
36. O. L. Phillips *et al.* Pattern and process in Amazon forest dynamics, 1976. *Philos. Trans. R. Soc. Ser. B* **359**, 381 (2004).
37. J. M. Metsaranta, W. A. Kurz, E. T. Neilson, G. Stinson, Implications of future disturbance regimes on the carbon

balance of Canada’s managed forest (2010–2100). *Tellus*, **62B**, 719 (2010).

38. M. Zhao, S. W. Running, Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, **329**, 940 (2010).

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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								2000-2007							
	Biomass	Dead Wood	Litter	Soil	Harvested wood product	Total stock change	Uncer-tainty(±)	Stock change per area	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**

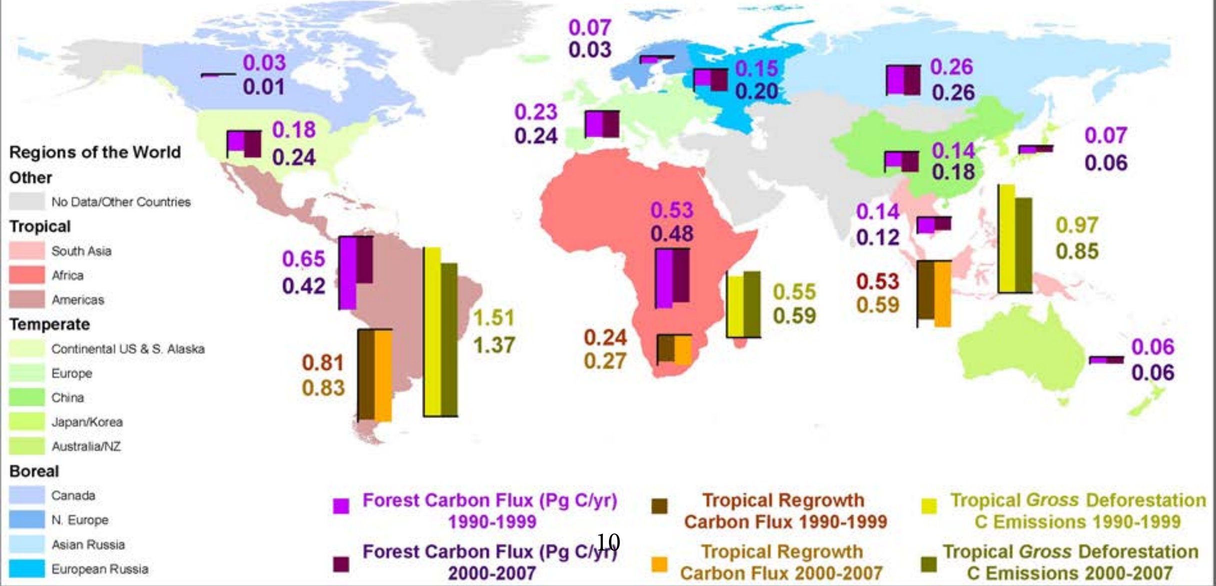
(1) Estimates include C stock changes on "forest land remaining forest land" and "new forest land" (afforested land); (2) The uncertainty calculation refers to the supporting online material; (3) ND means data not available and [1] litter is included in soils; (4) carbon outcomes of forest land-use changes (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.

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.



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

Supporting Online Material

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Methods and Data

Definitions of land categories

Forest- The definition of forest varies slightly from country to country, but generally follows the FAO definition: Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. Forest lands that are temporarily treeless because of harvest or disturbance are included. Forest does not include land that is predominantly under agricultural or urban land use, even though such land may have some tree cover. Tree plantations are included.

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

Afforestation- land that has changed from nonforest to forest.

Deforestation- land that has changed from forest to nonforest.

Tropical intact forest- tropical forest areas that have not been substantially affected by direct human activities.

Tropical regrowth forest- tropical forests regrowing on the areas that have been previously deforested or logged.

Forest Carbon Pools

We generally followed the definitions from Table 3.1.2 in the IPCC Good Practice Guidance *(1)*, though minor deviations are embedded in the data depending on specific national circumstances.

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

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

Litter – Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country (typically 10 cm), and lying dead biomass in various stages of decomposition above the mineral or organic soil. Includes the litter, fumic, and humic layers. Live fine roots may be included if excluded from living biomass.

Soil organic matter – Includes organic carbon in mineral and organic soils (including peat) to a specified depth of 1 meter. Live fine roots may be included if excluded from living biomass.

Carbon in harvested wood – includes products in use and in landfills. “Products in use” includes end-use products that have not been discarded or otherwise destroyed. Examples include residential and nonresidential construction, wooden containers, and paper products. “Products in landfills” includes discarded wood and paper placed in landfills where most carbon is stored long-term and only a small portion of the material is assumed to degrade, at a slow rate.

Overview of calculation methods and data

Accounting approaches to calculations for boreal, temperate, and tropical regions

There are slightly different accounting approaches used in this paper, in accordance with the IPCC guidelines, because the available data have been developed and presented in different ways in inventories, country reports, and the literature. Within the constraints of the available information, 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 here.

Either the “stock-change” or the “default” approaches were used for boreal and temperate biomes, following the guidance from IPCC for estimating and reporting country-level greenhouse gas inventories *(1,2)*. The stock change approach involves estimating C stocks at two or more points in time, then taking the difference between the stock estimates as the rate of change over the time period. If there is no land-use change, then this 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. We accounted for harvested wood products but not for other lateral transport, which may be responsible for a significant global C sink in coastal oceans *(3)* 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 nonforest land category and appear as a loss of C from forest. Because the area of afforestation is small relative to the total area of forest remaining forest, the effect is relatively small.

The IPCC default approach commences with a single forest inventory and then adds C gains from forest growth and losses from harvest, fires and decomposition *(1)*. The default approach (used in Canada's managed forests) accounts for C stock gains and losses without confounding estimates through C transfers between land-use categories.

For the tropics, 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 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 (harvesting did not take place on these land areas). The effects of land-use change and harvesting on C flux were estimated using a bookkeeping approach that keeps track of ecosystem C emissions and harvested wood products from deforestation and logging, and ecosystem C uptake on regrowing forests. Estimates of water transport and deposition are not accounted for in tropical forest biomes, though lateral transfers in harvested wood products were estimated.

Estimates of changes in C stocks for two periods (Table 2 of main text) pertain to "forest land remaining forest land" and "afforestation". Estimates of C stocks for specific years (Table S3) 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 Table 2. Thus, it is not possible to consistently match the estimates between these two tables.

Forest area and area change

Where available, area estimates (Table S2) are from country-level forest inventories or reports based on forest inventories. Forest inventories typically use remote sensing to estimate forest area and area changes. Where forest inventories are lacking, particularly in the tropics, FAO statistics were used to estimate total forest area for 1990, 2000, and 2007 *(4, 5)*. FAO statistics are compiled from country reports following established forest area definitions. Area estimates for 2007 based on FAO statistics were made by interpolating between the reported years 2005 and 2010. In some regions, particularly the tropics, the quality of the data reported to FAO is variable and the inventories may be subject to change and reinterpretation over time *(6,7)*. For tropical regions, updated area estimates for prior years were those reported in FAO *(5)*. Regarding area change, there is approximate consistency between the change in reported areas from the years 1990, 2000, and 2007, and estimated areas of afforestation and deforestation from inventories, country reports, and analyses of emissions from land-use change.

Carbon Stocks and Changes in Carbon Stocks

Where available, C stock and density estimates are from country-level forest inventories or reports based on forest inventories. Most countries in temperate and boreal biomes have established forest inventories 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. The measured data may be used to estimate the C stocks and changes in C stocks using a variety of country-specific methods described below, but following guidelines provided by IPCC *(1, 2)*.

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. For intact tropical forests, we used data from repeated long-term measurements of a network of ecological research plots, upscaled to the regions to estimate biomass and other C pools for the region's forest areas *(8, 9)*. For tropical regrowth forests, which lack sufficient ground-based data, we followed the bookkeeping approach *(10)* which is based on a literature review of regrowth rates and knowledge of forest areas and conditions. These methods are described in more detail below for each region.

The data from regions, countries or continents were aggregated to global biomes: boreal, temperate, and tropical forests. The boreal forest comprises Russia, Canada, and Northern Europe; the temperate forest includes the conterminous United States, Southeast Alaska, Europe except for the boreal countries, China, Japan, South Korea, Australia, and New Zealand; while the tropical forest encompasses south Asia, Africa and the Americas south of the United States. Available data allowed C stock and area estimates to be compiled for 1990, 2000, and 2007, and annual changes in C stocks (sometimes referred to as "flux" or "sink" in this paper) to be estimated for two time periods: 1990-1999 and 2000-2007. Five major forest C pools, including their densities and changes, were estimated in this study: live biomass (aboveground and belowground), dead wood (including dead trees and coarse woody debris), litter, soil organic matter, and harvested wood products.

More data are available for live biomass and biomass changes than for any 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. 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 the soil C estimates.

Harvested wood products

Where available, estimates of carbon in harvested wood products (HWP) are from country-level inventory reports as described above. Generally, estimates of carbon in HWP include both wood in use and discarded wood products remaining in landfills. For countries that lacked estimates of carbon in HWP, we derived a simple conversion factor from the countries that did report: the ratio of C in HWP (TgC yr^{-1}) to the quantity of harvested roundwood (million m^3) according to FAO reports *(4)*, which is 0.095.

Specific methods used for each country or regional estimates

Detailed descriptions of the methods for each region are presented here and summarized in table S1. In general, countries of the temperate zone have established forest inventories that provide a sound basis for estimating C stocks and changes in C stocks. Countries of the boreal zone typically have inventories of parts of the land that are more intensively managed for timber production or other services, and use remote sensing or models to supplement the inventory data for reporting to FAO or the United Nations Framework Convention on Climate Change (UNFCCC). For the tropics, there are very few countries that have established forest inventories, and reporting to FAO and UNFCCC is very limited. In the tropics, area estimates reported to FAO are the most consistent source for information about the extent of forest land, even though there have been changes in methods and reporting quality over the years.

Russia

Area estimates for 1990 and 2000 are derived from the official inventory data of the State Forest Account *(11-17)*; estimates for 2007 were updated from these inventories using remote sensing. Estimates of growing stock volume are based on official data of the State Forest Account for 1978-2009. These data have been corrected to eliminate biases of different methods of forest inventory which were applied in the country over the last three decades *(18, 19)* and to update obsolete inventory data for part of the country. Live biomass includes all components of forest ecosystems, not only trees *(20)*.

Carbon in harvested wood is based on official statistics in units of commercial wood. Data are recalculated to estimate growing stock volume removals (multiplying by a coefficient of 1.25), then converted to carbon. All types of harvest are included (final felling, thinning etc.). Estimates of illegal logging are not included. Estimated soil C is based on the latest assessment for 2007. Estimates for other years are based on empirical models that link soil C with amount of live biomass and level of disturbances *(19)*. The estimates for soil C include the 1m top layer below the organic layer (litter) and 1m for organic land (peat).

Estimated dynamics of C pools give results which are rather close to estimates of full C account for Russian forests based on flux-based methods *(21)*. The difference for the period of 2000-2007 is about 15-20%, which is mostly explained by some inconsistency in the account boundaries. The results of a recent reanalysis of the Russian forest C budget for 2003-2008 differ from the average of this study by 9% *(22)*.

Canada

Estimates of C stocks and C stock changes are obtained from Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) *(23)* developed to meet international reporting requirements for greenhouse gas emissions and removals in Canada's managed forest. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) *(24)* is the core model of NFCMARS. Details of data sources and regional results are provided elsewhere *(25)*. Information on deforestation is derived from a national deforestation monitoring program implemented for all of Canada's forests to meet the reporting requirements of the UNFCCC and the Kyoto Protocol. Because of data limitations, estimates of C stocks and stock changes are limited to the 230 Mha of managed forest, leaving unaccounted some 118 Mha of northern forests that are not subject to management.

The CBM-CFS3 is a well established C budget model used in Canada and internationally. It relies heavily on empirical data on forest conditions and forest changes, and simulates C stocks and stock changes in dead wood, litter and soil C as mass balances calculated from inputs (through litterfall, biomass turnover and disturbance inputs) and losses (through decomposition, transfers by harvesting, and losses to the atmosphere during disturbances such as fire) *(24, 25, 26)*. Following the recommendations of the IPCC, the model links dynamics of dead organic matter pools directly to the dynamics of the better-known biomass dynamics. At present, the CBM-CFS3 does not account for C stocks in forested wetlands with deep (peat) organic soils whose dynamics are strongly affected by water table fluctuations for which few data exist at the national scale.

Estimates of Harvested Wood Product (HWP) C stock changes are derived in part from a spreadsheet model developed by Environment Canada for the purposes of UNFCCC reporting. Estimates are based on the "production approach" which accounts for C stocks in HWP stocks derived from wood produced in Canada, regardless of their current location.

Alaska (the results are not included in the tables but inform the discussion)

Unlike the continental U.S., Alaska lacks an established forest inventory covering most of the State with repeated measurements. Therefore we used the Terrestrial Ecosystem Model (TEM), a process-based ecosystem model that uses spatially referenced information on atmospheric chemistry, climate, elevation, soils, and land cover to estimate monthly terrestrial carbon, nitrogen, and water fluxes and pool sizes. TEM is well-documented and has been used to examine patterns of terrestrial C dynamics across the globe and specifically applied to Alaska. For this study, we used a version of TEM modified from Felzer et al. *(27)*, which simulated ozone pollution effects, to also include the influence of permafrost dynamics *(28, 29)*, atmospheric nitrogen deposition, dissolved carbon (DOC) leaching, wildfire, pastures and timber harvest on terrestrial carbon dynamics.

The forest area estimate used in TEM (42.3 x 10^6 ha) is different from that reported in official U.S. forest statistics (51.3 x 10^6 ha, Smith et al. *(30)*). This difference is primarily because of difficulty in consistently classifying areas with sparse forest cover.

Continental United States.

Forest area estimates for specific years are from the United States (U.S.) Forest Inventory and Analysis (FIA) as reported for all lands of the continental U.S. and Southeast Alaska *(30)*. Estimated deforestation area is from the National Resources Inventory *(31)*. The area of afforestation was calculated as the area needed to account for the total area change after estimated losses from deforestation.

Estimates of forest C stocks in the U.S. are based on the U.S. Forest Service Forest Inventory and Analysis (FIA) data base. FIA statistics are compiled from a very large sample of U.S. forest lands – about 150,000 forested sample plots are inventoried on a rotating annual basis. Statistical estimates of forest area, species, and stand density are converted to ecosystem carbon estimates using standard procedures and following national and international accounting and reporting guidelines. Details of the methodology are available in USDA *(32)* and USEPA *(33)*, so only a brief overview is presented here. Forest tree biomass (live and dead) is estimated directly from the inventory measurements using allometric equations. Other C pools (down woody debris, forest floor, understory biomass, and soil C) are estimated using simple empirical models, parameterized from ecosystem studies that related these variables to observed forest characteristics from the inventory. Estimates of changes in soil C stocks account for a soil depth of one meter, and include the effects of land-use change and forest type shifts, but not increases or decreases on forest land that does not change forest types. The carbon in harvested wood (remaining in use and stored in landfills) is estimated using a model that converts removals data to C stocks based on tracking of wood processing and decay rate functions *(34)*.

The uncertainty of the estimated annual change in forest and wood products C is about 20% at the 95% confidence level *(33)*. These uncertainty estimates are based on a Monte Carlo uncertainty analysis of the mean estimates.

Europe

The data for Europe were obtained from the country reports prepared by 41 European countries for the Global Forest Resources Assessment of 2010 *(5)*. The quality and availability of forest area data for Europe is good. The reported values for forest area are generally based on field surveys from national forest inventories. In addition to reporting forest area, most countries also report annual (gross) rates of afforestation and the natural expansion of forest cover. Afforestation, in the terminology of this study, is the sum of these two rates of forest expansion. Deforestation can be inferred as the difference between net change forest area and afforestation. Eight countries lack values for annual afforestation. Depending on the sign of the net change of forest area in these countries, it is included in the regional totals as either afforestation or deforestation.

The estimates for carbon in living biomass in Europe are generally based on field surveys from national forest inventories that measure growing stock volume. Growing stock volume is converted to biomass, and biomass to carbon, using national factors developed by country-specific research or from IPCC's Good Practice Guidance *(1)*. The quality of these data is good.

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

The availability of data on C stocks in litter and soils is also limited. Of the 41 European countries included in the analysis, 27 reported soil C for at least one year (1990-2010). Nearly all European countries that report soil C use forest area based extrapolations. These estimates are constructed by either applying a constant ratio of soil C per hectare to total forest area, or by applying ratios specific to soil type and soil type areas. Three countries deviate from this practice. In Austria and Sweden, soil C estimates are based on inventory data. In Finland, soil C stocks are principally estimated using the Yasso model. The soil depth at which soil C was measured varied between countries. Of the countries that had data, 17 used a soil depth of 30 cm. In the remaining 10 countries, the soil depth applied in estimates varies from 20 cm (in Belgium) to 100 cm (in Finland and the UK).

In this study, the C stocks in litter and soils for countries that lacked data were estimated by using area-based litter and soil C ratios. For countries that lacked data for some year(s), these ratios were extrapolated based on data for other years. For countries entirely lacking data, these ratios were adopted from the country with the most similar climate and forest use history. In these cases, the estimated ratios were constant and based on data from 1990. Available estimates were adjusted to a standard depth of one meter if a different depth was used, based on a model of soil C by depth reported in Jobbagy and Jackson *(35)*. Estimates of the HWP C stock changes were derived using the method described earlier in the general methods section.

<u>China</u>

We estimated forest biomass C stock and its change during the 1990s and 2000s for China, using biomass expansion factors for each forest type and China's forest inventory data for the periods 1989-1993, 1994-1998, 1999-2003, and 2004-2008 *(36, 37)*. Since 1994, the definition of forest in China's forest inventory has changed from >30% canopy coverage to >20% canopy coverage. We therefore calculated forest area, C density, and C change for 1989-1993 based on the new criterion (20% canopy coverage). Analyzing the 1994-1998 inventory data that provide both criteria (20% and 30% canopy coverage), we found that there exists a robust linear relationship for the forest area and timber volume between the two criteria at the provincial level (Equations 1 and 2).

$$AREA_{0.2} = 1.183 AREA_{0.3} + 12.137 \quad (R^2 = 0.990, n=30) \qquad (1)$$
$$TC_{0.2} = 1.122 TC_{0.3} + 1.157 \quad (R^2 = 0.995, n=30) \qquad (2)$$

where $AREA_{0.2}$ and $AREA_{0.3}$ are forest areas (10^4 ha) in a province under the two forest criteria, >20% and >30% canopy coverage, respectively; $TC_{0.2}$ and $TC_{0.3}$ are total forest C stocks in province under the two criteria. The provincial forest areas and C stocks with the new criterion in 1989-1993 were calculated based on Equations 1 and 2, followed by derivation of the corresponding forest C densities for the different C pools *(36)*. Carbon in soil to a depth of one meter was estimated using ratios of soil C to vegetation biomass.

<u>Japan and Korea</u>

A number of field measurements of forest biomass and systematic national forest inventories in Japan made it possible to estimate the C stocks and their changes. Allometric relationships between forest biomass (above- and below-ground) and stem volume (biomass expansion factors) were first obtained for the major forest types in Japan from 945 sets of direct field measurements across the country. These relationships were used to estimate the changes in C accumulation of aboveground biomass and total living biomass from 1990 to 2005 using the national forest inventories of 1985, 1990, 1995, 2000, and 2005 *(38)*. Soil C and changes in soil C were estimated using ratios of soil C to vegetation biomass. Litter C stocks and changes were not estimated. An approach similar to that used for Japan was used to estimate C stocks and changes for Korea *(39)*.

Australia and New Zealand

Australia designed a systematic national forest inventory in the mid-1990s, though no data were available for this study. However, the country has published Australia's State of the Forest Report (ASFR) every 5 years since 1998 *(40)*. The 2008 report includes a special section for reporting the contribution of forest ecosystems to global greenhouse gas balance, with relatively complete information back to 1989. In the carbon section, the basic information of forest areas, area of deforestation, area of new plantations, forest biomass (above-ground plus roots), soil C (litter plus below-ground carbon), C sequestration and timber harvesting in managed native and plantation forests are provided. Australia also has the annual inventory reports of forest plantations, Australia's UNFCCC report *(41)*, and Australia's National Greenhouse Accounts *(42)* with detailed information of land-use, land-use change and forestry that are tracked back to 1990. These available data were used in combination and carefully cross-checked to produce the information for this study. During the calculation procedure, the data from different reports were often used to fill each other's data gaps. Also, the data in the first two ASFRs are not as complete as in the 2008 report. Therefore, some information, for instance, the ratios of biomass and soil C for different forest types, was employed to calculate the soil C component which was not included in the earlier reports. Because managed native forest in Australia is about 75% of total native forest, it is possible that the carbon values estimated in this study could be lower than the reality.

New Zealand, similar to Australia, has published the country reports of forests titled "Sustainable Management of New Zealand's Forests" *(43, 44)*. The 2009 report included a special section to report forest contribution to the global C cycle with data of 2000, 2003 and 2008 for indigenous and plantation forests, including forest C pools and fluxes. In the other sections of the report, more information, such as forest areas, productivity, and harvesting, is provided. In contrast to Australia, New Zealand has very little timber harvest from native forests because industrial plantation forests provide sufficient quantities of wood products. Besides the data in the forest report, we used New Zealand's UNFCCC reports and the National Greenhouse Gas Inventory *(45)* to provide extra information such as annual forest land C flux from 1990-2007. The data from different resources were cross-checked and used to supplement each other to produce the estimates in this study. For instance, there are detailed data of different C pools (C in above-ground biomass, below-ground biomass, coarse woody debris, fine woody debris and little) for plantation and indigenous forests in 2005. Therefore, the ratios were calculated and applied to estimate corresponding components for years 1990 and 2000 to meet the requirements of this study.

Intact Forests of Tropical America, Africa, and Asia

Area estimates for intact tropical forests for each region were made by subtracting the area of secondary tropical regrowth forests estimated by Houghton et al. *(46)*, and Houghton *(10, 47)* from the total area of forests reported in FRA 2010 *(5)*. To estimate areas for 2007, we interpolated between the reported areas for 2005 and 2010.

Carbon stock and stock change estimates are based on a network of permanent sample plots in each of Africa and Tropical America, while for Tropical Asia, where we lack sufficient sample sizes, we estimate changes in carbon stocks using the mean change rate of Tropical American and African forests. Methods for permanent plot work in Tropical America and Africa, and data quality control, are detailed elsewhere *(8, 9, 48, 49)*. We developed a database *(50)* in which we curate several hundred tree-by-tree long-term forest demographic datasets from across the tropics (http://www.forestplots.net/). We assume that the same proportional net change detected in biomass in trees ≥10cm diameter is also expressed in the same proportion in all biomass compartments that are not monitored directly (shrubs, saplings and lianas, below-ground, necromass, and litter). We do not account for possible changes in soil C stocks or harvested wood C stocks (for estimates of these pools, see sections in general methods describing soils and harvested wood products).

For Tropical America the total sample size is 135 plots, with a median size of 1 ha, mean census intervals of about four years, and mean total census length of about 12 years. We estimate mean net fluxes over a multi-decadal period prior to 2000 using all plot data earlier than that date, using the data and methods presented in Phillips et al. 2009 (census date approx 1980-2000).

In 2005 we detected a strong reversal of the Amazon biomass sink *(8)*, but here derive a biomass change estimate for the 2000-2006 period within which time the forest was still projected to be a net sink, albeit a weaker one than in previous decades and with greater uncertainty due to the shorter monitoring period.

For Africa the underlying data was published in Lewis et al. *(9)*, from 79 plots spanning 10 African countries, with a median plot size of 1 ha, a mean start and end date of 1987 and 1997. We derived a single multi-decade aboveground biomass change rate because the data are insufficient to split into two time periods and obtain an unbiased mean change in biomass due to the non-normal distribution of biomass change in tropical forests *(9)*. This mimimal sample size requirement is discussed for Africa in Lewis et al.*(9)*, for Amazonia by Gloor et al. *(51)*, and more generally in Lloyd et al. *(52)*.

For tropical Asia there are insufficient available, published data to provide an unbiased on-the-ground estimate of biomass change in mature forests. We therefore estimated the tropical Asian change using the mean of the proportional annual change rates for Africa (0.31%) and

South America (0.28%), which we then applied to all biomass compartments for each of the two periods, 1990-2000 and 2000-2007.

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

The C stock data (biomass, deadwood, litter and soil) are incomplete with data only available for 2000 from Africa and South America. We used C stocks of 2000 and flux data of 1990-1999 and 2000-2007 to calculate C stocks for 1990 and 2007. First, we rebuilt the C stock of 2000 for tropical Asia. We used the average C density of tropical Africa and America as the C density of tropical Asia (for each C pool), and multiplied the density and the forest area to estimate the C stock of 2000 for tropical Asia. In estimating the C stocks, we considered the effect of C fluxes and also the loss of intact forest areas on C stocks. The calculation routine was performed for each C pool and each region. To make the description simple, we present here the general calculation routine. For the stock in 1990, the cumulative C sink over 1990-1999 was subtracted from the stock of 2000, then the C density was calculated (based on the forest area in 2000), resulting in our estimate of the C density of 1990. Then the C stock in 1990 was calculated based on the C density and the forest area in 1990 (i.e. a larger area), resulting in our estimate of the C stock of 1990. For the stock in 2007, the cumulative C sink over 2000-2007 (8 years) was added to the stock of 2000. Then the new C density was calculated (based on the forest area in 2000), resulting in our estimate of the C density of 2007. Then the C stock in 2007 was calculated based on the C density and the forest area (i.e. a smaller area), resulting in our estimate of the C stock of 2007.

Overall we have high confidence in a substantial long-term sink in intact tropical forests (Amazonia and Africa), notably because sample sizes are large enough to detect such an effect *(51)*, but low confidence in any trends or comparisons amongst regions, and extremely low confidence in estimates for Asia.

Methods for Tropical Regrowth Forests of America, Africa, and Asia

We based our estimates for tropical regrowth forests on data reported in Houghton et al. *(46)*, and Houghton *(10, 47)*, recently updated to include revised estimates of tropical forest areas reported in the Forest Resources Assessment 2010 *(5)*. This approach allowed our estimates to be consistent with estimates of CO_2 emissions from deforestation when we aggregated the results of our study with the other sources and sinks of the global C cycle (table 3 in the main text), which are based on forest areas reported by FAO.

The areas of tropical regrowth forests for 1990, 2000, and 2005 for each region were based on data reported in Houghton et al. *(46)*, and Houghton *(10, 47)*. We adjusted the area estimates in these reports to be consistent with the revised estimates for previous years reported in Forest Resources Assessment 2010 *(5)*. To estimate areas for 2007, we interpolated between the reporting years 2005 and 2010. We estimated gross areas of afforestation and deforestation (rather than net change in land use) based on data from Houghton et al. *(46)*, and Houghton *(10, 47)*.

For estimating C stocks and stock changes for tropical regrowth forests, we used the stock change estimates reported by Houghton et al.*(46)*, and Houghton *(10, 47)*. In these studies, total C stocks and changes in C stocks, on a per-area basis, were developed from literature estimates of forest regrowth. The stock-change estimates reported in these studies were supplemented with additional unreported detail from the data bases used in the bookkeeping approach. We estimated total C stocks for the 3 regions and reporting years 1990, 2000, and 2005 for live biomass, dead wood, and soils. To estimate stocks for 2007, we extrapolated based on the rate of change from 2000 to 2005.

To validate our estimates of stock changes, we compared the growth estimates for tropical regrowth forests with other estimates from the literature (Table S4). Our estimates are comparable to those recommended by IPCC and to other literature sources for tropical Asia and America, but lower than other estimates for Africa, primarily because of the larger proportion of dry forest area in Africa. Because of the lack of statistical surveys and permanent sample plots, the uncertainty of estimated values for secondary tropical forests is very significant, estimated by expert opinion to be as high as ±50%. The level of 50% for the 95% confidence level (see the following section for uncertainty estimation) was chosen for two reasons: (i) the uncertainties were greater than those estimated for tropical intact forests, which were derived directly from measurement data (except for S. America over 2000-2007 because of a great uncertainty for the Amazon drought effect on forest C uptakes in the intact forests); and (ii) the uncertainties are consistent with the widely reported uncertainty (0.7 Gt C/yr) in tropical land-use emission (that variable includes regrowth offset). Other levels such as 25% and 75% did not fit these criteria.

Approaches to estimate uncertainty

We report the Standard Error 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.

Where possible we used quantitative estimates of uncertainty, either calculated from sample plot data or reported in the source of data using an acceptable calculation method. If quantitative estimates of uncertainties were not available from the source data or could not be calculated, we derived them from expert opinion using the following uncertainty scale, which has been used in previous large-scale analyses *(55)*.

(1) 95% certain that the actual value is within 10% of the estimate reported
(2) 95% certain that the estimate is within 25%
(3) 95% certain that the estimate is within 50%
(4) 95% certain that the estimate is within 75%
(5) 95% certain that the estimate is within 100%

These are informed categorizations, reflecting expert judgment, using all known descriptions of uncertainty surrounding the "best available" or "most likely" estimate. If multiple expert opinions were available, we used the highest uncertainty among them. In addition, we firstly estimate an uncertainty scale for carbon stock changes based on data or "expert opinions". Then we used 50% of the scale to evaluate uncertainty of C stocks with an assumption that uncertainty for estimating C stock changes (the difference between two stocks) is the sum of uncertainties of stocks.

Main sources of uncertainty

Area

Generally, forest area estimates from countries with forest inventories are accurate (reported estimate within 5% of the true value), and the estimated net change between reporting years, calculated as the difference between successive estimates, is also accurate. However, it is often difficult to estimate the gross changes in area – afforestation and deforestation – because these estimates tend to be a small percentage of the total forest area and therefore require intensified sampling methods that may not be operationally deployed. For areas lacking forest inventories, particularly the tropics, there are well-known problems with reported estimates particularly regarding temporal consistency *(6)*. Many reports from tropical countries are not based on remote sensing or sample surveys, but use subjective expert assessment -- 33% of countries according to Grainger *(6)*. Updating older data, a common practice, also produces errors, as does re-estimating data for older reporting years if methods or definitions change. The separation of total tropical forest area by region into intact and regrowth forests is ambiguous with respect to accounting for small-scale selective logging, because these areas are difficult to detect from remote sensing and therefore are not clearly distinguished as part of the area of forest regrowth, which includes recovery from large-scale logging.

Carbon Stocks and Changes in Carbon Stocks

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

Supplemental Results, Tables and Figures

Global forest area

Detailed information about the area of global forests, by country/biome and year, including estimates of afforestation and deforestation, is shown in Table S2. The largest area of forest land is in the tropics, followed by boreal and then temperate forests. Globally, the area of forest land declined by 3% between 1990 and 2007, due to the loss of primary tropical forest, which exceeded gains in area of boreal and temperate forests, and increasing area of secondary forest. Afforestation was greatest in temperate forests especially in the U.S., Europe, and China. The Asian part of Russia also showed a large gain in area due to afforestation. Deforestation was significantly greater in the tropics, though there were significant areas deforested in the temperate zone particularly the U.S. and Australia.

Area estimates reported here are consistent with the global forest area reported by FAO *(4, 5)* for 1990, 2000, and 2010, except that we estimate less reduction in total forest area over time (Table S5). This is primarily because of higher estimates of afforestation in Russia than included in the total forest area of the FAO Forest Resources Assessment.

Forest carbon stocks and change in stocks for regions and pools

Supporting information about the C stock of global forests, by country/biome and year, including details for the major C pools, is shown in Table S3. Analysis of global forest C stocks and changes in global forest C stocks for boreal, temperate, and primary tropical forests is presented in the main text. We estimated C sequestration rates (Table 2 of main text) and C densities (Table S3) in different regions and countries, which are useful data although we did not fully analyze them in the main text. Here, we include some detailed analyses of C stocks and changes to supplement the information presented in the main text. We also briefly describe knowledge of changes in C stocks for “unmanaged” areas of the Northern Hemisphere that were excluded from our tables.

Alaska and Northern Canada
Large areas of unmanaged forests in the Northern Hemisphere lack sufficient ground data for reporting changes in C stocks in a way that is consistent with the other estimates reported here. Estimates reported for boreal forests exclude 51 Mha of Interior Alaska and 118 Mha

of Northern Canada. These areas are typically remote and not directly affected in a significant way by human activities including fire suppression. Thus, changes in C stocks of these areas are dominated by natural disturbance cycles. Modeling studies, which have a basis in ground data but not from statistical surveys, reveal that these areas are likely to be in near equilibrium with respect to C emissions and sinks. Boreal forests of Alaska were estimated to be a small C sink of 0.01 PgCyr^{-1} in previous studies *(56, 57)*; however, some modeling results prepared for this study show a C source, which has increased from 0.005 Pg C yr^{-1}in the 1990s to 0.014 Pg C yr^{-1} in the 2000s, caused by carbon release from litter and soils under fires and warming (considering deeper soils than used in other areas of this study), offsetting the small amount of C sequestration in biomass. Compared to the large C sink in forests of the European part of Russia, the boreal forests of North America are only small sinks or sources.

Russia

The C sink in Russian forests increased by 15% between 1990-1999 and 2000-2007 (Table 2 in main text). Asian Russia, with vast forest lands and a lower average C sequestration rate compared with European Russia, had the largest boreal sink, but that sink increased only slightly (Fig. 1 in main text) because of increased emissions from wildfire disturbances, resulting in reduced litter (-32%) and soil (-6%) sinks, and an increased deadwood sink (+46%) *(58)*. In contrast, there was a much larger sink increase of 35% in European Russia (Fig. 1 in main text), particularly involving biomass (+129%). The large C sink increase in the European Russian forests is 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 in European Russia and the middle taiga *(58)*.

Japan, South Korea and Oceanic Countries

In Japan and South Korea, forests have the greatest average C sequestration rates among the major temperate countries because of a suitable oceanic climate for fast forest growth and effective application of forest management practices (Table 2 in main text) *(38)*. However, while forests of South Korea had an increased sink over the decades due to a young forest age structure, the sink in Japan declined as the forests aged towards maturity. In Australia and New Zealand, natural forests are generally close to equilibrium state with relatively low C sequestration rates *(40, 43)*. Drought and wildfire as well as deforestation in primary forests of Australia caused a slightly decreased C sink in biomass in the 2000s. Reported increases in total C sinks (Table 2 in main text) are primarily due to afforestation in the two countries, and a significant C increase in harvested wood products, particularly in New Zealand.

Tropical intact forests

The magnitude of the C sink of African intact forests was comparable to that of tropical American forests, despite a smaller area (494 Mha vs. 773 Mha). This implies a high C sequestration rate over the large area of tropical African forests (Table 2) *(59)*. The C sink in intact forests of tropical Asia is less than one-third of that in other continents because only about 40% of forested areas remain as intact forests *(5)*, much less than in tropical Africa (~70%) and America (~80%) (Table S2). However, there is large uncertainty associated with the estimated C uptake in tropical Asia because of a scarcity of long-term field data.

The reduced C uptake between 1990-1999 and 2000-2007 due to the shrinking area of tropical intact forest is 19%, 9% and 6% for tropical Asia, Africa and America, respectively. But this decreasing sink is partially compensated by C gains in tropical regrowth forests (Table 2, Fig.1 in main text). There was a 30% decline of the C sink in tropical America in 2000-2007 due to one severe drought year, which greatly affected the decadal estimate of C sink for whole tropics and reflected the sensitivity of the tropical forests to climate extremes. However, the full decadal impact of the drought on the Amazon C balance remains uncertain because data are incomplete for the post-drought period *(8)*.

Deadwood, litter and soils

These variables are most often excluded from the global budget or forest inventory analyses. Compared with living biomass, there is usually higher uncertainty in estimating these components, both stocks and fluxes, because of insufficient data. However, these C stocks and fluxes provide critical information about carbon dynamics and structures of forest ecosystems that enable better understanding of the impacts of environmental drivers and disturbances.

Globally, dead wood is estimated to be a small but significant component of the forest C stock (8% of total, Table S3), and the estimated C sink in dead wood accounts for more than 10% of the total C sink in forests (Table 2). The estimated sink in deadwood C stocks has increased by 36% over two decades. The significant increase of the C sink in the dead wood in boreal forests (147%) makes a major but possibly transient contribution to the total C sequestration in the high latitudinal belt, since decomposition could exceed creation of new dead wood in the future, induced by soil warming and increased wildfires in the region. In temperate forests, a substantial part of which is intensively managed, the deadwood C sink is only 10% of the living biomass sink, and has not changed over two decades, in stark contrast to boreal forests. In intact tropical forests, the deadwood sink is also about 10% of the living biomass sink. Therefore, the global increase of deadwood simply reflects a trend in boreal forests.

The global soil C stocks are likely underestimated, especially for ecosystems with deep organic soils such as boreal peatlands and tropical mangroves. The magnitude and direction of change in deep soil C stocks in forests is currently unknown. The C sink in litter is larger in boreal forests, roughly equivalent to the soil sink. The global litter and soil stock of C is distributed 51%, 34% and 15% respectively in boreal, tropical and temperate forests, compared with the biomass stock allocation of 16%, 70% and 14%, revealing the fundamental differences of C structure in biomes. The C sink in litter and soil accounts for

~16% of the total global sink and has declined by 12% globally over two decades, with a stable sink in the temperate region, and declines in other regions.

Global carbon budget

Different accounting schemes are used to describe the elements of the global C budget, which could be confusing. In the main text (Table 3), the budget was based on accounting for C sources and sinks. The two major C sources include fossil fuel emissions and the emissions from global land-use changes. The three major reservoirs for C sinks include atmosphere, ocean and terrestrial biosphere (land). In this way, the C emissions from land-use change (also from land) is also used to constrain the remaining terrestrial sink, which is in fact significantly larger since accounting includes the net loss from land-use change.

There is another way to account for the elements of the global C budget (Table S6) based on major earth systems. The land-system is constrained by fossil fuel emissions and sinks of ocean and atmosphere. The C losses from land-use changes are balanced by C uptake of lands within the system. The terrestrial sink is a *net* sink and seems smaller than the size based on the accounting of the above method. However, this is only because the terrestrial sink in Table 3 (main text) is a *gross* terrestrial sink. No matter which way is used in accounting for the global C budget, it is important to be clear about the definitions of each component and how they are combined.

References

1. IPCC. *Good practice guidance for land use, land-use change, and forestry* (IGES, Japan, 2003; http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html)
2. IPCC, *IPCC guidelines for national greenhouse gas inventories* (IGES, Japan, 2006; http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html).
3. P. Ciais, A.V. Borges, G. Abril, M. Meybeck, G. Folberth *et al*. The impact of lateral carbon fluxes on the European carbon balance. *Biogeosciences* **5(5)**, 1259-1271 (2008)
4. Food and Agriculture Organization, *Global forest resources assessment 2005* (Forestry Paper 147, Food and Agriculture Organization, Rome, 2006).
5. Food and Agriculture Organization, *Global forest resources assessment 2010* (Forestry Paper 163, Food and Agriculture Organization, Rome, 2010).
6. A. Grainger. Difficulties in tracking the long-term global trend in tropical forest area. *Proc. Natl. Acad. Sci. U.S.A.* **105(2)**, 818–823 (2008)
7. P. E. Waggoner. *Forest inventories: discrepancies and uncertainties,* (Discussion paper. Washington, DC, Resources for the Future, 2009).
8. O. L. Phillips, L. E. Aragão, S. L. Lewis, J. B. Fisher, J. Lloyd et al., Drought sensitivity of the Amazon rainforest. *Science* **323**, 1344-1347 (2009).
9. S. L. Lewis, G. Lopez-Gonzalez, B. Sonké, K. Affum-Baffo, T.R. Baker, Increasing carbon storage in intact African tropical forests. *Nature* **477**: 1003-1006 (2009).
10. R. A. Houghton, Balancing the global carbon budget. *Annual Review of Earth and Planetary Science* **35**, 313-347 (2007).
11. FFS 1995. “Forest Fund of Russia (state by January 1, 1993)” (Federal Forest Service of Russia, Moscow, 1995) (official data in Russian, access by title).
12. FFS 1999. “Forest Fund of Russia (state by January 1, 1998)” (Federal Forest Service of Russia, Moscow, 1999) (official data in Russian, access by title).
13. FFS 2003. “Forest Fund of Russia (state by January 1, 2003)” (Federal Forest Service of Russia, Moscow, 2003) (official data in Russian, access by title).
14. FFS 2005. “Forest Fund of Russia (state by January 1, 2005)” (Federal Forest Service of Russia, Moscow, 2005) (official data in Russian, access by title).
15. Goscomles USSR 1982. “Forest Fund of the USSR (state by January 1, 1978)” (USSR State Committee of Forest Management, Moscow, 1982) (in Russian, access by title)
16. Goscomles USSR 1986. “Forest Fund of the USSR (state by January 1, 1983)” (USSR State Committee of Forest Management, Moscow, 1986)(in Russian, access by title)
17. Goscomles USSR 1990. “Forest Fund of the USSR (state by January 1, 1988)” (USSR State Committee of Forest Management, Moscow, 1990) ([in Russian, access by title)
18. A. Shvidenko, S. Nilsson. Dynamics of Russian forests and the carbon budget in 1961-1998: An assessment based on long-term forest inventory data. *Climatic Change* **55**, 5-37 (2002)
19. A. Shvidenko, S. Nilsson. A synthesis of the impact of Russian forests on the global carbon budget for 1961-1998. *Tellus* **55B**, 391-415 (2003)

20. A. Shvidenko, D. Schepschenko, S. Nilsson, Y. Bouloui. Semi-empirical models for assessing biological productivity of Northern Eurasian forests. *Ecological Modelling*, **204**, 163-179 (2007)
21. A. Shvidenko, D. Schepaschenko, I.McCallum, F. Kraxner, S.Nilsson, S. Maksyutov. Verified terrestrial ecosystems full carbon account for Russia: A reanalysis, in Proceedings *of the 8th International CO2 Conference* (Jena, September 2009, CD Rom)
22. A. Shvidenko, D. Schepaschenko, S. Maksyutov. Impact of terrestrial ecosystems of Russia on global carbon cycle in 2003-2008: An attempt of synthesis, in *Proceedings of the International Science Conference* (ENVIROMIS 2010, 5-12 July, Tomsk, Russia), pp 48-52.
23. W. A. Kurz, M.J. Apps. Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to meet the reporting requirements of the Kyoto Protocol. *Mitigation and Adaptation Strategies for Global Change*, **11**, 33–43 (2006).
24. W. A. Kurz, C.C. Dymond, T.M. White, G. Stinson, C. H. Shaw *et al.*. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* **220**, 480-504 (2009)
25. G. Stinson, W. A. Kurz, C. E. Smyth, E. T. Neilson, C. C. Dymond, et al. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Glob. Change Bio.*, DOI: 10.1111/j.1365-2486.2010.02369 (2010)
26. W. A. Kurz, M. J. Apps. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* **9(2)**, 526-547 (1999).
27. B. Felzer, D. Kicklighter, J. Melillo, C. Wang, Q. Zhuang, R. Prinn. Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus* **56B,** 230-248 (2004)
28. Q. Zhuang, A. D. McGuire, J. M. Melillo, J. S. Clein, R. J. Dargaville *et al.* Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th Century: A modeling analysis of the influences of soil thermal dynamics, *Tellus,* **55(B)**, 751-776 (2003)
29. E. S. Euskirchen, A. D. McGuire, D. W. Kicklighter, Q. Zhuang, J. S. Clein et al. Importance of recent shifts in soil thermal dynamics on growing season length, productivity and carbon sequestration in terrestrial high-latitude ecosystems. *Global Change Biology* **12(4)**, 731-750 (2006)
30. W. B. Smith, P.D. Miles, C.H. Perry, S.A. Pugh. "Forest Resources of the United States, 2007" (Gen. Tech. Rep. WO-78. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office, 2009).
31. USDA. "Summary Report: 2007 National Resources Inventory" (Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, 2009; http://www.usda.gov/oce/global_change/AFGGInventory1990_2005.htm)
32. USDA. *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005* (Technical Bulletin No. 1921, Global Change Program Office, Office of the Chief Economist, U.S. Department of Agriculture, 2008)

33. U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007* (EPA 430-R-09-004, 2009; http://www.epa.gov/climatechange/emissions/usinventoryreport.html)
34. K. Skog, Sequestration of carbon in harvested wood products for the United States. *For Prod J* **58(6),** 56–72 (2008)
35. E. G. Jobbágy, R.B. Jackson. The vertical distribution of organic soil carbon and its relation to climate and vegetation. *Ecological Applications* **10(2)**, 423-436 (2000)
36. J. Y. Fang, A. P. Chen, C.H. Peng, S. Q. Zhao, L. Ci, L. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* **292**, 2320–2322 (2001).
37. J. Y. Fang, Z. D. Guo, S. L. Piao, A. P. Chen. Terrestrial vegetation carbon sinks in China, 1981–2000. *Sci. China Ser. D*, **50**, 1341–1350 (2007).
38. J. Fang, O. Takehisa Oikawa, T. Kato, W. Mo, Z. Wang. 2005. Biomass carbon accumulation by Japan's forests from 1947 to 1995. *Global Biogeochemical Cycles*, **19** (2005)
39. S-D. Choi, K. Lee, Y-S. Chang. Large rate of uptake of atmospheric carbon dioxide by planted forest biomass in Korea *Global Biogeochem. Cycles,* **16,** 1089 (2002)
40. ASOFR. "Australia's State of the Forests Report" ((http://adl.brs.gov.au/forestsaustralia/publications/sofr2008.html, 1998, 2003, 2008) (Accessed December 11, 2010)
41. UNFCCC. "Australia's UNFCCC report" (http://unfccc.int/files/methods_and_science/lulucf/application/pdf/australia.pdf, 2007) (Accessed December 11, 2010)
42. AGEIS. "Australia's National Greenhouse Accounts" (http://www.climatechange.gov.au/climate-change/emissions.aspx, updating with time, 2009) (Accessed December 11, 2010)
43. MAF. *Sustainable management of New Zealand's forests* (Ministry of Agriculture and Forestry; http://www.maf.govt.nz/mafnet/publications/2008-nz-report-montreal-process/index.htm, 2009) (Accessed December 11, 2010)
44. MAF. *A Forestry Sector Study* (Ministry of Agriculture and Forestry; http://www.maf.govt.nz/forestry/publications/forestry-sector-study-2009/, 2009) (Accessed December 11, 2010)
45. New Zealand Ministry for the Environment. *New Zealand's Greenhouse Gas Inventory1990–2007* (http://www.mfe.govt.nz/publications/climate/greenhouse-gas-inventory-2009/index.html, 2009) (Accessed December 11, 2010)
46. R. A. Houghton, D. L. Skole, C. A. Nobre, J. L. Hackler, K. T. Lawrence et al. Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature* **403**, 301-304 (2000)
47. R. A. Houghton. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus* **55B**, 378-390 (2003)
48. O. L. Phillips, T. Baker, L. Arroyo, N. Higuchi, T. Killeen et al. Pattern and process in Amazon forest dynamics, 1976-2001. *Philosophical Transactions of the Royal Society, Ser. B* **359**, 381-407 (2004)

49. O. L. Phillips, S. L. Lewis, T. R. Baker, K.-J. Chao, N. Higuchi. The changing Amazon forest. *Philosophical Transactions of the Royal Society, Ser.B.* **363**, 1819-1828 (2008).
50. J. Peacock, T. Baker, S. L. Lewis, G. Lopez-Gonzalez, O. L. Phillips. The RAINFOR database: monitoring forest biomass and dynamics. *Journal of Vegetation Science* **18**, 535-542 (2007)
51. M. Gloor, O. L. Phillips, Y. Malhi, J. J. Lloyd, S. L. Lewis et al. Is the disturbance hypothesis for explaining trends in Amazonian forest biomass consistent with basin-wide data? *Glob. Change Bio.* **15**, 2418–2430 (2009).
52. J. Lloyd, E. Gloor, S. L. Lewis. Are the dynamics of tropical forests dominated by large and rare disturbance events? *Ecology Letters* **12**, E19–E21 (2009)
53. D. J. Zarin, M. J. Ducey, J. M. Tucker.Potential biomass accumulation in Amazonian regrowth forests. *Ecosystems* **4**: 658-668 (2001).
54. F. Achard, H. D. Eva, P. Mayaux, H-J Stibig, A. Belward. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles* **18**: GB (2008).
55. CCSP. *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*, A. W. King, L. Dilling, G.P. Zimmerman, D.M. Fairman, R.A. Houghton *et al* Eds. (U.S. Climate Change Science Program and the Subcommittee on Global Change Research, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 2007)
56. J. Yarie, S. Billings. 2002. Carbon balance of the taiga forest within Alaska: present and future. *Can. J. For. Res.* **32**, 757–767 (2002)
57. A. D. McGuire, M. Apps, F. S. Chapin III, R. Dargaville, M. D. Flannigan et al. Land cover disturbances and feedbacks to the climate system in Canada and Alaska., in *Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface, G.* Gutman, A. C. Janetos, C. O. Justice, E. F. Moran, J. F. Mustard et al. Eds. (Dordrecht, Netherlands, Kluwer, 2004), pp. 139-161.
58. A. Z. Shvidenko, D. G. Schepaschenko, S. Nilsson, Materials to perception of current productivity of forest ecosystems in Russia. In *Basic Problems of Transition to Sustainable Forest Management in Russia,* V. A. Sokolov, A. Z. Shvidenko, O. P. Vtorina Eds (Russian Academy of Sciences, Krasnoyarsk 2007), pp. 5-35.
59. E. T. A. Mitchard, S. S. Saatchi, I. H. Woodhouse, G. Nangendo, N. S. Ribeiro *et al.* Using satellite radar backscatter to predict above-ground woody biomass: A consistent relationship across four different African landscapes, *Geophys. Res. Lett.*, 36, L23401 (2009)

Table S1. Summary of methods and main sources of data for estimating area, carbon stocks, and carbon stock changes, country/region.

Country/ Region	**Forest area and changes in forest area**	**Carbon stocks and changes in carbon stocks**	**References**
Russia	Forest inventory data updated with remote sensing	Modified forest inventory data converted to carbon with biomass equations and ecosystem carbon models	FFS 1995, 1999, 2003,2005; Shvidenko and Nilsson 2002, 2003
Canada	Forest inventory data and deforestation monitoring. Note: 118 Mha of unmanaged northern forests not included.	Carbon budget model combines forest inventory data, growth and yield data, and data on natural disturbances, forest management, and land-use change, with climate and ecological data.	Kurz and Apps 2006; Kurz et al. 2009
Alaska	SE Alaska temperate forests included with rest of U.S. temperate forests. Note: 51 Mha of unmanaged northern forests not included.	Forest carbon flux estimates from a terrestrial ecosystem model (not included in results but described in supplemental material).	Smith et al. 2009; Felzer et al. 2004
United States	Forest Inventory data combined with National Resources Inventory (all lands) data	Forest inventory data converted to carbon with biomass equations and ecosystem carbon models	USDA 2008; Smith et al. 2009; U.S. EPA 2009
Europe	FAO Forest Resources Assessment	Biomass expansion factors applied to convert volume estimates from FAO. Various methods employed for other C pools.	FAO 2006; IPCC 2006, Liski et al. 2002
China	Forest inventory data	Biomass expansion factors applied to convert volume estimates from inventory data.	Fang et al. 2001, 2007
Japan	Forest inventory data	Biomass expansion factors applied to convert volume estimates from inventory data.	Fang et al. 2005
South Korea	Forest inventory data	Biomass expansion factors applied to convert volume estimates from inventory data.	Choi et al. 2002
Australia	Remote sensing estimates	Estimates from “State of the Forest” reports.	ASFR 1998, 2003, 2008
New Zealand	Remote sensing estimates	Estimates from “Sustainable Management” reports.	MAF 2009
Asia	FAO Forest Resources Assessment	Intact forests: C density estimates extrapolated from other tropical regions. Regrowth forests: bookkeeping model	FAO 2010 Houghton 2007
Africa	FAO Forest Resources Assessment	Intact forests: permanent plot network for C density. Regrowth forests: bookkeeping model	FAO 2010 Houghton 2007 Lewis et al. 2009
Americas	FAO Forest Resources Assessment	Intact forests: permanent plot network for C density. Regrowth forests: bookkeeping model	FAO 2010 Houghton 2007 Phillips et al. 2008, 2009

Table S2. Area of forests and land-use change by biome, country or region, and year or period (1,2)

Biome and country /region	Total forest area, 1990	Total forest area, 2000 (Mha)	Total forest area, 2007	1990-1999 Afforestation	1990-1999 Deforestation (Mha yr^{-1})	1990-1999 Net change	2000-2007 Afforestation	2000-2007 Deforestation (Mha yr^{-1})	2000-2007 Net change
Boreal (3)									
Asian Russia	658.6	662.6	676.6	0.500	0.100	0.400	1.825	0.075	1.750
European Russia	155.7	159.2	169.0	0.450	0.100	0.350	1.300	0.075	1.225
Canada	230.1	229.7	229.4	0.007	0.052	-0.044	0.003	0.047	-0.044
Europe boreal (4)	58.3	59.1	60.2	0.085	0.000	0.085	0.165	0.037	0.128
Subtotal	**1102.7**	**1110.6**	**1135.2**	**1.042**	**0.252**	**0.791**	**3.293**	**0.234**	**3.059**
Temperate (3)									
United States (5)	245.7	251.7	257.0	1.000	0.400	0.600	1.107	0.350	0.757
Europe	132.0	140.1	144.5	0.865	0.060	0.805	0.777	0.091	0.686
China	139.3	142.8	155.6	4.452	0.000	4.452	4.223	0.000	4.223
Japan	23.8	23.5	23.6	ND	ND	-0.028	ND	ND	0.019
South Korea	6.5	6.4	6.3	ND	ND	-0.006	ND	ND	-0.024
Australia	154.6	150.8	149.2	0.060	0.439	-0.379	0.075	0.397	-0.322
New Zealand	7.8	8.3	8.3	0.056	0.008	0.048	0.015	0.014	0.001
Other countries	15.7	15.7	16.0	ND	ND	-0.008	ND	ND	0.036
Subtotal	**733.6**	**746.1**	**766.7**	**6.433**	**0.907**	**5.346**	**6.197**	**0.852**	**5.285**
Tropical Intact (6)									
South Asia	190.6	136.9	124.9	ND	ND	-5.364	ND	ND	-1.719
Africa	600.2	531.9	494.0	ND	ND	-6.835	ND	ND	-5.402
Americas	885.2	817.2	773.2	ND	ND	-6.798	ND	ND	-6.279
Subtotal	**1675.9**	**1486.0**	**1392.2**	**ND**	**ND**	**-18.997**	**ND**	**ND**	**-13.400**
Global Subtotal (7)	**3512.3**	**3342.7**	**3294.1**	**7.475**	**1.159**	**-12.861**	**9.490**	**1.086**	**-5.056**
Tropical Regrowth (8)									
South Asia	134.8	164.2	172.4	ND	ND	2.934	ND	ND	1.176
Africa	149.0	176.8	190.6	ND	ND	2.775	ND	ND	1.982
Americas	163.2	182.3	194.2	ND	ND	1.908	ND	ND	1.696
Subtotal	**447.1**	**523.2**	**557.2**	**ND**	**ND**	**7.617**	**ND**	**ND**	**4.854**
All Tropics									
South Asia	325.4	301.1	297.3	1.070	3.500	-2.430	2.457	3.000	-0.543
Africa	749.2	708.6	684.7	0.340	4.400	-4.060	0.880	4.300	-3.420
Americas	1048.4	999.5	967.4	0.710	5.600	-4.890	0.217	4.800	-4.583
Subtotal	**2123.0**	**2009.2**	**1949.4**	**2.120**	**13.500**	**-11.380**	**3.554**	**12.100**	**-8.546**
Global Total (9)	**3959.3**	**3865.9**	**3851.3**	**9.595**	**14.659**	**-5.244**	**13.044**	**13.186**	**-0.202**

(1) The total area of forest land in a reported year includes “forest land remaining forest land” and “new forest land” (afforested land); (2) ND means data not available; (3) Deforested land (forest that was changed to non-forest) is excluded from the area total; land that is harvested or disturbed but still defined as forest land is included in the area total; (4) Includes Norway, Sweden, and Finland; (5) Includes Southeastern part of Alaska; (6) The tropical forest land that has not been substantially disturbed by direct human activities; (7) Global established forest lands that include forest remaining forest over the study periods plus afforestated land in boreal and temperate biomes, plus intact forest in the tropics; (8) Tropical forest lands regrowing from past deforestation and logging; (9) Tropical forest lands that include tropical intact forest and regrowth forest; and (9) Areas excluded from this table include Interior Alaska (51 Mha in 2007), Northern Canada (118 Mha in 2007), West/Central Asia (43 Mha), and "other wooded land" reported to FAO.

Table S3. Forest Carbon stocks by biome, country or region for 1990, 2000 and 2007 (1, 2, 3)

Biome and country/region	1990							2000							2007						
	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncert-ainty (±)	Carbon density (Mg C ha^{-1}	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncert-ainty (±)	Carbon density (Mg C ha^{-1}	Total living biomass	Dead wood	Litter	Soil	Total C stock	Uncert-ainty (±)	Carbon density (Mg C ha^{-1}
	(Pg C)							(Pg C)							(Pg C)						
Boreal																					
Asian Russia	26.6	7.4	9.8	115.5	159.4	19.9	242.0	27.2	8.0	10.2	117.2	162.7	20.3	245.5	27.9	8.8	10.5	120.1	167.3	20.9	247.3
European Russia	8.3	2.0	2.9	24.2	37.4	4.7	240.5	8.8	2.1	3.2	25.0	39.1	4.9	245.7	9.6	2.3	3.3	26.7	42.0	5.2	248.5
Canada	14.4	5.0	11.5	19.7	50.6	6.3	219.8	14.4	4.8	11.6	19.7	50.5	6.3	220.0	14.0	5.0	11.7	19.7	50.4	6.3	219.7
Europe boreal	2.2	0.1	1.3	7.6	11.2	1.3	191.6	2.3	0.1	1.4	8.0	11.7	1.3	198.1	2.5	0.1	1.4	7.9	11.8	1.3	196.2
Subtotal	**51.5**	**14.5**	**25.6**	**167.0**	**258.6**	**21.5**	**234.5**	**52.8**	**15.0**	**26.4**	**169.9**	**264.0**	**21.9**	**237.7**	**53.9**	**16.1**	**27.0**	**174.5**	**271.5**	**22.5**	**239.2**
Temperate																					
United States	17.2	2.5	4.6	15.7	40.0	3.8	162.8	18.4	2.6	4.7	15.8	41.5	3.9	164.8	19.4	2.7	4.8	16.0	42.9	4.1	167.1
Europe	8.4	0.3	1.9	15.0	25.5	2.6	193.4	9.5	0.3	2.0	15.8	27.6	2.8	197.1	10.5	0.3	2.0	16.3	24.0	3.0	166.4
China	5.3	0.1	1.1	14.3	20.8	2.6	149.5	5.9	0.1	1.1	15.0	22.1	2.8	154.6	6.5	0.1	1.2	16.3	24.2	3.0	155.5
Japan	1.3	ND	ND	ND	1.3	0.2	52.5	1.5	ND	ND	ND	1.5	0.2	63.8	1.6	ND	ND	ND	1.6	0.2	66.4
South Korea	0.1	ND	ND	ND	0.1	<0.1	19.3	0.2	ND	ND	ND	0.2	<0.1	29.0	0.2	ND	ND	ND	0.2	<0.1	29.8
Australia	6.3	ND	3.7	5.3	15.4	1.9	99.7	6.5	0.0	3.8	5.5	15.8	2.0	105.0	6.6	0.0	3.9	5.6	16.1	2.0	108.1
New Zealand	1.2	0.1	0.1	0.7	2.1	0.3	269.8	1.3	0.1	0.1	0.7	2.1	0.3	256.5	1.3	0.1	0.1	0.7	2.2	0.3	259.1
Other countries	0.4	ND	0.1	1.8	2.3	0.6	145.4	0.5	ND	0.1	1.8	2.3	0.6	145.8	0.5	ND	0.1	1.8	2.3	0.6	146.4
Subtotal	**40.3**	**3.1**	**11.4**	**52.7**	**107.6**	**5.7**	**146.7**	**43.7**	**3.2**	**11.8**	**54.5**	**113.1**	**6.0**	**151.6**	**46.6**	**3.3**	**12.1**	**56.7**	**118.6**	**6.3**	**154.7**
Tropical Intact																					
South Asia	28.7	5.9	0.5	15.6	50.6	6.6	265.6	21.6	4.3	0.4	11.2	37.5	4.9	274.1	20.4	4.0	0.4	10.2	35.0	4.5	280.1
Africa	84.7	18.9	1.4	43.0	147.9	42.0	246.4	79.4	17.2	1.3	38.1	136.0	38.6	255.7	76.6	16.2	1.2	35.4	129.5	36.8	262.1
Americas	141.5	27.0	2.7	81.3	252.5	32.1	285.2	136.2	25.4	2.5	75.1	239.1	30.4	292.6	131.2	24.2	2.4	71.0	228.8	48.2	295.9
Subtotal	**254.8**	**51.7**	**4.5**	**139.9**	**451.0**	**53.2**	**269.1**	**237.2**	**46.9**	**4.2**	**124.4**	**412.6**	**49.4**	**277.7**	**228.2**	**44.4**	**4.0**	**116.6**	**393.3**	**60.8**	**282.5**
Global Subtotal (4)	**346.7**	**69.3**	**41.5**	**359.7**	**817.1**	**57.7**	**232.7**	**333.7**	**65.0**	**42.3**	**348.8**	**789.8**	**54.3**	**236.3**	**328.7**	**63.8**	**43.1**	**347.8**	**783.4**	**65.1**	**237.8**
Tropical Regrowth																					
South Asia	15.0	3.5	[1]	14.3	32.9	8.2	243.7	19.7	4.0	[1]	17.8	41.5	10.4	252.6	22.8	5.0	[1]	19.6	47.4	11.8	274.7
Africa	1.9	1.0	[1]	5.5	8.4	2.1	56.4	2.3	1.1	[1]	6.3	9.7	2.4	54.9	2.6	1.7	[1]	7.1	11.4	2.8	59.6
Americas	3.0	2.4	[1]	4.2	9.6	2.4	59.1	5.3	2.2	[1]	5.9	13.5	3.4	73.8	8.6	2.3	[1]	8.1	19.0	4.7	97.7
Subtotal	**19.8**	**7.0**	**0.0**	**24.1**	**50.9**	**8.8**	**113.8**	**27.3**	**7.3**	**0.0**	**30.0**	**64.6**	**11.2**	**123.5**	**33.9**	**9.1**	**0.0**	**34.7**	**77.7**	**13.1**	**139.4**
All Tropics																					
South Asia	43.6	9.4	0.5	29.9	83.5	10.6	256.5	41.3	8.3	0.4	29.0	79.0	11.5	262.3	43.2	9.1	0.4	29.8	82.4	36.9	277.0
Africa	86.6	19.9	1.4	48.5	156.3	42.0	208.6	81.8	18.3	1.3	44.4	145.7	38.7	205.6	79.2	18.0	1.2	42.5	140.9	48.4	205.7
Americas	144.5	29.4	2.7	85.5	262.1	32.2	250.0	141.5	27.6	2.5	81.0	252.6	30.6	252.7	139.8	26.5	2.4	79.1	247.8	62.2	256.1
Subtotal	**274.7**	**58.7**	**4.5**	**164.0**	**501.9**	**54.0**	**236.4**	**264.5**	**54.2**	**4.2**	**154.4**	**477.3**	**50.6**	**237.5**	**262.1**	**53.6**	**4.0**	**151.3**	**471.0**	**93.0**	**241.6**
Global Total (5)	**366.5**	**76.3**	**41.5**	**383.7**	**868.0**	**58.3**	**219.2**	**361.0**	**72.3**	**42.3**	**378.8**	**854.4**	**55.5**	**221.0**	**362.6**	**72.9**	**43.1**	**382.5**	**861.1**	**66.4**	**223.6**

(1). Carbon stocks for the total area of forest land in a reported year, which includes “forest land remaining forest land” and “new forest land” (afforested land); (2) The soil depth is at 1 meter. (3) ND: no data available and [1] litter is included in soil; (4) Estimates of carbon stocks for global established forests; (5) Estimates of carbon stocks for specific years pertain to the total area of forest land in the given year and therefore include lost carbon stocks because of deforestation. Thus, it is not possible to consistently match the estimates of stock change in Table 3 (main text) that pertain to “forest land remaining forest land” and “afforestation”.

Table S4. Comparison of estimates of above-ground biomass increment (Mg C ha^{-1}yr^{-1}) on tropical regrowth forests.

Tropical region	Estimates used in this study	IPCC estimates[1]	Other references
America	3.8	3.6	3.4 (Zarin et al. 2001)*(53)*
Africa	1.0	2.3	3.4 (Houghton et al. 2000)*(46)*
Asia	3.3	3.5	3.8 (Achard et al. 2004)*(54)*

[1] Intergovernmental Panel on Climate Change "Good Practice Guidance" *(2)*.

Table S5. Comparison of area estimates, this study and FAO Forest Resources Assessment 2010

	Total forest area, 1990	Total forest area, 2000 (Mha)	Total forest area, 2007
Forest area included in C analysis	3959.3	3865.9	3851.3
Forest areas excluded from C analysis			
Canada unmanaged forest	118.0	118.0	118.0
Alaska unmanaged forest	51.0	51.0	51.0
West/Central Asia	41.5	42.2	43.0
Subtotal	210.5	211.2	212.0
Global Total, This study	**4169.8**	**4077.1**	**4063.3**
Global Total, FRA 2010	**4168.4**	**4085.2**	**4049.8**

Table S6. Global C budget accounting based on earth systems (1, 2)

Sources and Sinks(1)	1990-1999	2000-2007
Atmosphere /ocean:		
Fossil fuel and cement	6.5±0.4	7.6±0.4
Atmosphere	3.2±0.1	4.1±0.1
Ocean	2.2±0.4	2.3±0.4
Terrestrial Residuals	1.1±0.6	1.2±0.6
Terrestrial (Global forests) (2):		
Tropical *gross* deforestation	3.0±0.5	2.9±0.5
Tropical forest regrowth	1.6±0.5	1.7±0.5
Tropical land-use change	1.5±0.7	1.1±0.7
Established Forests	2.5±0.4	2.3±0.5
Global *net* forest sink	1.0±0.8	1.2±0.8
Global residuals :	0.1±1.0	0.0±1.0

(1) Red colors are sources, and black colors are sinks

(2) The results are from this study (Table 1 of main text), we used the estimates of global forests as a proxy for the terrestrial sink.