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Why are estimates of the terrestrial carbon balance so different?

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Abstract

The carbon balance of the world's terrestrial ecosystems is uncertain. Both top-down (atmospheric) and bottom-up (forest inventory and land-use change) approaches have been used to calculate the sign and magnitude of a net terrestrial flux. Different methods often include different processes, however, and comparisons can be misleading. Differences are not necessarily the result of uncertainties or errors, but often result from incomplete accounting inherent in some of the methods. Recent estimates are reviewed here. Overall, a northern mid-latitude carbon sink of approximately 2 Pg C yr^{-1} appears robust, although the mechanisms responsible are uncertain. Several lines of evidence point to environmentally enhanced rates of carbon accumulation. Other lines suggest that recovery from past disturbances is largely responsible for the sink. The tropics appear to be a small net source of carbon or nearly neutral, and the same uncertainties of mechanism exist. In addition, studies in the tropics do not permit an unequivocal choice between two alternatives: large emissions of carbon from deforestation offset by large sinks in undisturbed forests, or moderate emissions from land-use change with essentially no change in the carbon balance in undisturbed forests. Resolution of these uncertainties is most likely to result from spatially detailed historical reconstructions of land-use change and disturbance in selected northern mid-latitude regions where such data are available, and from systematic monitoring of changes in the area of tropical forests with satellite data of high spatial resolution collected over the last decades and into the future.

Keywords: carbon balance, carbon sink, forest inventories, global carbon budget, land-use change, terrestrial ecosystems

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Introduction

The net flux of carbon between terrestrial ecosystems and the atmosphere is uncertain. Historically, the annual emissions of carbon from fossil fuels, the rate of growth of carbon dioxide in the atmosphere, and the uptake of carbon by the oceans suggested that terrestrial ecosystems were a small carbon sink (Bacastow & Keeling, 1973). Calculations of a net release of carbon from changes in land use required an even larger terrestrial sink to balance the carbon cycle (Woodwell *et al.*, 1978; Houghton *et al.*, 1983). Over the last decade several new methods, including two top-down and two bottom-up methods, have been used to estimate the net terrestrial flux of carbon. All four methods appear to yield different results, some differing even as to the direction of flux. The methods include different terrestrial processes, however, and a comparison of estimates may reveal the mechanisms responsible for some of the sources and sinks of carbon. The purpose of this paper is to review these recent estimates and to evaluate what mechanisms are suggested.

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Top-down estimates

At least two top-down methods have been used to determine terrestrial sources and sinks of carbon. Both are based on atmospheric concentrations of CO_2. The first method uses concentrations of O_2 as well as CO_2 to partition atmospheric sinks of carbon between land and ocean (Keeling *et al*., 1996; Battle *et al*., 2000). The latest IPCC assessment (Prentice *et al*., 2001) used results from this method to evaluate the global carbon balance. According to the assessment, terrestrial ecosystems, globally, were a net sink for carbon, averaging 0.2 ($\pm$ 0.7) $Pg\,C\,yr^{-1}$ in the 1980s and 1.4 ($\pm$ 0.7) $Pg\,C\,yr^{-1}$ in the 1990s. The reason for a large increase in the terrestrial sink between the 1980s and 1990s is unknown. Also unexplained is the apparent decrease in the net oceanic sink from the 1980s to the 1990s. Given the larger emissions from fossil fuels and the higher atmospheric concentration of CO_2 in the second decade, one would have expected the oceans to take up more carbon, not less. The partitioning of the sink between land and ocean over the period 1990–2000 included a small correction for the outgassing of O_2 from the oceans (Prentice *et al*., 2001).

A more recent analysis by Plattner *et al*. (2002) determined that outgassing was much larger than estimated by Prentice *et al*. (2001). The recalculated partitioning between land and sea (Table 1) shows a larger oceanic uptake in the 1990s than the 1980s and a terrestrial uptake more similar between decades (an average decadal difference of 0.3, rather than 1.2, $Pg\,C\,yr^{-1}$). The net terrestrial flux averaged 0.4 and 0.7 $Pg\,C\,yr^{-1}$ (as compared to 0.2 and 1.4 $Pg\,C\,yr^{-1}$) during the 1980s and 1990s, respectively. The revised estimates of the oceanic sink are consistent with the results of oceanic models (Plattner *et al*., 2002).

A second top-down approach (inverse modeling) uses atmospheric transport models, together with spatial and temporal variations in atmospheric concentrations of CO_2 obtained through a network of flask air samples, to infer surface sources and sinks of carbon. A recent analysis using this inverse approach calculated a global terrestrial sink of 1.4 $Pg\,C\,yr^{-1}$ for the years 1992–1996 (Gurney *et al*., 2002), higher than that obtained from changes in O_2 and CO_2 (0.7 $Pg\,C\,yr^{-1}$) (Plattner *et al*., 2002). However, the estimate from the inverse approach has to be adjusted to account for terrestrial sources and sinks of carbon that are not 'seen' by the atmosphere. For example, the budget will not accurately reflect changes in the amount of carbon on land or in the sea if some of the carbon fixed by terrestrial plants or used in weathering minerals is transported by rivers to the ocean and respired or released to the atmosphere there. Under such circumstances, the atmosphere sees a terrestrial sink and an oceanic source, while the storage of carbon on land and in the sea may not have changed. Several studies have tried to adjust atmospherically based carbon budgets by accounting for the river transport of carbon. Sarmiento & Sundquist (1992) estimated a preindustrial net export by rivers of 0.4–0.7 $Pg\,C\,yr^{-1}$, balanced by a net terrestrial uptake of carbon through photosynthesis and weathering. Aumont *et al*. (2001) recently obtained a global estimate of 0.6 $Pg\,C\,yr^{-1}$. Adjusting the net terrestrial sink obtained through inverse calculations (1.4 $Pg\,C\,yr^{-1}$) by 0.6 $Pg\,C\,yr^{-1}$ yields a result (0.8 $Pg\,C\,yr^{-1}$) similar to the first top-down estimate obtained through changes in the concentrations of O_2 and CO_2 (Table 2). The two top-down methods based on atmospheric measurements yield similar global estimates of a net terrestrial sink ($\sim$ 0.7 ($\pm$ 0.8) $Pg\,C\,yr^{-1}$ for the 1990s).

This net terrestrial balance is not evenly distributed over the land surface. A recent intercomparison of 16 atmospheric transport models (the TransCom 3 project) showed a net terrestrial sink of 2.4 ± 0.8 $Pg\,C\,yr^{-1}$ for northern mid-latitude lands, offset to some degree by a net tropical land source of 1.2 ± 1.2 $Pg\,C\,yr^{-1}$ (Gurney *et al*., 2002) (Table 3). River transport and subsequent oceanic release of terrestrial material are thought to overestimate the magnitude of the atmospherically derived northern terrestrial sink by 0.3 $Pg\,C\,yr^{-1}$ and underestimate the tropical source (or overestimate its sink) by the same magnitude (Aumont *et al*., 2001). Thus, the northern terrestrial sink becomes 2.1 $Pg\,C\,yr^{-1}$, while the tropical terrestrial source becomes 1.5 $Pg\,C\,yr^{-1}$ (Table 2).

Table 1 Global carbon budgets for the 1980s and 1990s ($Pg\,C\,yr^{-1}$)

	1980s	1990s
Fossil fuel emissions*	5.4 ± 0.3	6.3 ± 0.4
Atmospheric increase*	3.3 ± 0.1	3.2 ± 0.2
Oceanic uptake†	-1.7 ± 0.6	-2.4 ± 0.7
Net terrestrial flux†	-0.4 ± 0.7	-0.7 ± 0.8
Land-use change‡	2.0 ± 0.8	2.2 ± 0.8
Residual 'terrestrial' flux	-2.4 ± 1.1	-2.9 ± 1.1

Negative values indicate a withdrawal of CO_2 from the atmosphere.
*from Prentice *et al*. (2001).
†from Plattner *et al*. (2002).
‡from Houghton (in press).

Bottom-up estimates

At least two other methods, independent of those based on atmospheric data and models, have been used to estimate terrestrial sources and sinks of carbon over large regions: analyses of forest inventories and analyses of land-use change. Forest inventories provide systematic measurement of wood volumes from more than a million plots throughout the northern temperate-zone and boreal forests. One recent synthesis of these forest inventories, after converting wood volumes to total biomass and accounting for the fate of harvested products and changes

Table 2 Estimates of the annual terrestrial flux of carbon ($Pg\,C\,yr^{-1}$) in the 1990s according to different methods

	O_2 and CO_2	Inverse calculations CO_2, $^{13}CO_2$, O_2	Forest inventories	Land-use change
Globe	−0.7 (±0.8)*	−0.8 (±0.8)†	–	2.2 (±0.6)‡
Northern mid-latitudes	–	−2.1 (±0.8)§	−0.6 to −1.3¶	−0.03 (±0.5)‡
Tropics	–	1.5 (±1.2)**	−0.6 (±0.3)††	0.5–3.0‡‡

Negative values indicate a terrestrial sink.
*Plattner *et al*. (2002).
†−1.4 (±0.8) from Gurney *et al*. (2002) reduced by 0.6 to account for river transport (Aumont *et al*., 2001).
‡Houghton (in press).
§−2.4 from Gurney *et al*. (2002) reduced by 0.3 to account for river transport (Aumont *et al*., 2001).
¶−0.65 in forests (Goodale *et al*., 2002) and another 0.0–0.65 assumed for nonforests (see text).
**1.2 from Gurney *et al*. (2002) increased by 0.3 to account for river transport (Aumont *et al*., 2001).
††Undisturbed forests: −0.6 from Phillips *et al*. (1998) (challenged by Clark, 2002).
‡‡0.9 (range 0.5–1.4) from DeFries *et al*. (2002), 1.3 from Achard *et al*. (2002) adjusted for soils and degradation (see text), 2.2 (±0.8) from Houghton (in press), 2.4 from Fearnside (2000).

Table 3 Terrestrial sources (+) and sinks (–) of carbon ($Pg\,C\,yr^{-1}$) estimated by different methods

Region	Inversions based on atmospheric data and models (Gurney *et al*., 2002) (1992–1996)	Analysis of land-use change (Houghton, in press) (1990s)	Forest inventories (Goodale *et al*., 2002) (~1990)
Globe	−1.4 (±0.8)	2.2 (±0.8)	
North	−2.4 (±0.8)	−0.03 (±0.5)	−0.65 (±0.05)
Tropics	1.2 (±1.2)	2.2 (±0.8)	
South	−0.2 (±0.6)	0.02 (+0.2)	

in pools of woody debris, forest floor, and soils, found a net northern mid-latitude terrestrial sink of between 0.6 and 0.7 $Pg\,C\,yr^{-1}$ for the years around 1990 (Goodale *et al*., 2002). The estimate is about 30% of the sink inferred from atmospheric data corrected for river transport (Table 2). Some of the difference may be explained if non-forest ecosystems throughout the region are also accumulating carbon (see below). It is also possible that the accumulation of carbon below ground, not directly measured in forest inventories, was underestimated and thus might account for the difference in estimates. However, the few studies that have measured the accumulation of carbon in forest soils have consistently found soils to account for only a small fraction (5–15%) of measured ecosystem sinks (Gaudinski *et al*., 2000; Barford *et al*., 2001; Schlesinger & Lichter, 2001). Thus, despite the fact that the world's soils hold two to three times more carbon than biomass, there is no evidence yet that they account for much of a terrestrial sink.

The discrepancy between estimates obtained from forest inventories and inverse calculations might also be explained by differences in the dates of measurements. The northern sink of 2.1 $Pg\,C\,yr^{-1}$ from Gurney *et al*. ($-2.4+0.3$ for riverine transport) is for 1992–1996 and would probably have been lower (and closer to the forest inventory-based estimate) if averaged over the entire decade (see other estimates in Prentice *et al*. (2001)). Top-down measurements based on atmospheric data are sensitive to large year-to-year variations in the growth rate of CO_2 concentrations.

A second type of bottom-up estimate is obtained from analyses of land-use change. Changes in land use suggest that deforestation, reforestation, cultivation, and logging were responsible for a carbon source, globally, that averaged 2.0 $Pg\,C\,yr^{-1}$ during the 1980s, and 2.2 $Pg\,C\,yr^{-1}$ during the 1990s (Houghton, in press).

The approach includes emissions of carbon from the decay of dead plant material, soil, and wood products and sinks of carbon in regrowing ecosystems, including both vegetation and soil. Analyses account for delayed sources and sinks of carbon that result from decay and regrowth following a change in land use. The calculated *source* of 2.2 (±0.8) $Pg\,C\,yr^{-1}$ for the 1990s is very different from the global net terrestrial *sink* determined from top-down analyses (0.8 $Pg\,C\,yr^{-1}$) (Table 2).

Analyses of land-use change may yield higher terrestrial sources and/or lower terrestrial sinks than other methods because of bias in the methods. Forest inventories clearly ignore large areas of nonforest lands, although other data may be used to determine carbon fluxes for these types of ecosystems (see below). Biases in the inverse calculations may be in either direction. Because of the 'rectifier effect' (the seasonal covariance between the terrestrial carbon flux and atmospheric transport), inverse calculations are thought to underestimate the magnitude of a northern mid-latitude sink (Denning *et al*., 1995). On the other hand, if the near-surface concentrations of atmospheric CO_2 in northern mid-latitude regions are naturally lower than those in the southern hemisphere, the apparent sink in the north may not be anthropogenic, as usually assumed. Rather, the anthropogenic sink would be less than 0.5 Pg C yr^{-1} (Taylor & Orr, 2000).

In contrast to the unknown bias of atmospheric methods, analyses based on land-use change are deliberately biased. These analyses consider only the changes in terrestrial carbon resulting directly from human activity (conversion and modification of terrestrial ecosystems). There may be other sources and sinks of carbon not related to land-use change (such as caused by CO_2 fertilization or changes in climate) that are captured by other methods but ignored in analyses of land-use change. In other words, the flux of carbon from changes in land use is not necessarily the same as the net terrestrial flux from all terrestrial processes. The deliberate bias is illustrated in the next section.

A residual (terrestrial) flux of carbon

If the net terrestrial flux of carbon during the 1990s was 0.7 Pg C yr^{-1}, and 2.2 Pg C yr^{-1} were emitted as a result of changes in land use and management, then 2.9 Pg C yr^{-1} must have accumulated on land for reasons not related to land-use change. This gross sink is called the residual terrestrial sink (Table 1) (formerly it was called the missing sink). The carbon released from land-use change and the residual sink sum to the observed net sink. That the residual terrestrial sink exists at all suggests that processes other than land-use change are affecting the storage of carbon on land. On the other hand, the residual sink is calculated by difference; if the emissions from land-use change are overestimates, the residual sink will also be high.

The northern temperate zones

Insights into the mechanisms responsible for the residual terrestrial flux of carbon may be obtained from a consideration of tropical and extra-tropical regions separately.

For the US alone (Table 4), Houghton *et al*. (1999) estimated a carbon sink of 0.15–0.35 Pg C yr^{-1} attributable to changes in land use. Pacala *et al*. (2001) revised the estimate upwards by including additional processes, but in so doing they included sinks not necessarily resulting from land-use change or management. Their estimate for the uptake of carbon by forests, for example, was the uptake measured by forest inventories. The measured uptake might result from previous land use (regrowth), but it might also result from environmentally enhanced growth, for example CO_2 fertilization (Fig. 1). If all of the accumulation of carbon in US forests were the result of recovery from past land-use practices (that is, no enhanced growth), then the measured uptake should equal the flux calculated on the basis of land-use change. The residual flux would be zero. The study by Caspersen *et al*. (2000) suggests that such an attribution is warranted because they found that 98% of forest growth in five US

Table 4 Estimated rates of carbon accumulation in the US (Pg C yr^{-1} in 1990)

	Pacala *et al*. (2001)*				
	Low	High	Houghton *et al*. (1999)†	Houghton (in press)†	Goodale *et al*. (2002)
Forest trees	−0.11	−0.15	−0.072‡	−0.046§	−0.11
Other forest organic matter	−0.03	−0.15	0.010	0.010	−0.11
Cropland soils	0.00	−0.04	−0.138	0.00	NE
Woody encroachment	−0.12	−0.13	−0.122	−0.061	NE
Wood products	−0.03	−0.07	−0.027	−0.027	−0.06
Sediments	−0.01	−0.04	NE	NE	NE
Total sink	−0.30	−0.58	−0.35	−0.11	−0.28
% of total sink neither in forests nor wood products	43%	36%	74%	55%	NE

NE is 'not estimated'. Negative values indicate a source of carbon to the atmosphere.

*Pacala *et al*. (2001) also included the import/export imbalance of food and wood products and river exports. As these would create corresponding sources outside the US, they are ignored here.

†Includes only the direct effects of human activity (i.e. land-use change and some management).

‡0.020 Pg C yr^{-1} in forests and 0.052 Pg C yr^{-1} in the thickening of western pine woodlands as a result of early fire suppression.

§0.020 Pg C yr^{-1} in forests and 0.026 Pg C yr^{-1} in the thickening of western pine woodlands as a result of early fire suppression.

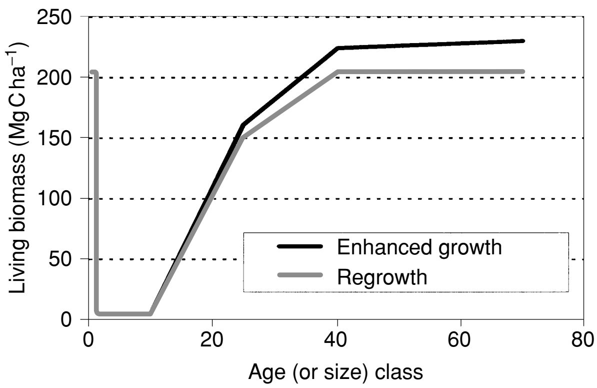

Fig. 1 Idealized curves showing the difference between enhanced growth and regrowth in accounting for the accumulation of C in aboveground tree biomass.

states could be attributed to regrowth rather than enhanced growth. However, the analysis by Houghton *et al*. (1999) found that past changes in land use accounted for only 20–30% of the observed accumulation of carbon in trees. The uptake calculated for forests recovering from agricultural abandonment, fire suppression, and earlier harvests was only 20–30% of the uptake measured by forest inventories. The percentage becomes 65% if the uptake attributed to woodland 'thickening' (0.52 Pg C yr^{-1}) is included (Table 4). Nevertheless, the results appear to be inconsistent with those of Caspersen *et al*. (2000). Houghton's analysis requires a significant growth enhancement to account for the observed accumulation of carbon in trees; the analysis by Caspersen *et al*. (2000) suggests little enhancement.

Both analyses merit closer scrutiny. Joos *et al*. (2002) have pointed out, for example, that the relationship between forest age and wood volume (or biomass) is too variable to constrain the enhancement of growth to between 0.001 and 0.01% per year, as Caspersen *et al*. claimed. An enhancement of 0.1% per year fits the data as well. Furthermore, even a small enhancement of 0.1% per year in net primary production yields a significant sink ($\sim$2 Pg C yr^{-1}) if it applies globally (Joos *et al*., 2002). Thus, Caspersen *et al*. may have underestimated the sink attributable to enhanced growth.

On the other hand, Houghton's analyses of land-use change (Houghton *et al*., 1999; Houghton, in press) most likely underestimate the sink attributable to re-growth. Houghton did not consider forest management practices other than harvest and subsequent regrowth. Nor did he include natural disturbances, which in boreal forests are more important than logging in determining the current age structure and hence, rate of carbon accumulation (Kurz & Apps, 1999). A third reason why the sink may have been underestimated is that Houghton used net changes in agricultural area to obtain rates of agricultural abandonment. In contrast, rates of clearing and abandonment are often simultaneous and thus create larger areas of regrowing forests than would be predicted from net changes in agricultural area. At present it is unclear how much of the carbon sink in the US can be attributed to changes in land-use and management, and how much can be attributed to enhanced rates of growth.

One of the findings common to Houghton *et al*. (1999) and Pacala *et al*. (2001) is that nonforest ecosystems seem to account for a significant carbon sink. Between 36 and 43% of the net sink estimated by Pacala *et al*. and 55–74% of that estimated by Houghton *et al*. is in nonforests.

Houghton (in press) has revised some of the earlier estimates (Table 4). Initially, Houghton *et al*. (1999) reported a sink of 0.138 Pg C yr^{-1} in agricultural soils, an upper limit of 0.12 Pg C yr^{-1} in woody encroachment, and an upper limit of 0.052 Pg C yr^{-1} in the thickening of woodlands. Subsequent analyses of the accumulation of carbon in agricultural soils as a result of conservation tillage indicate a much reduced response (0.0–0.4 Pg C yr^{-1}) (Schimel *et al*., 2000; Pacala *et al*., 2001) and more conservative estimates for woody encroachment and woodland thickening are half the upper limits. Studies show, for example, that grasses are displacing woody plants in some ecosystems (Billings, 1990), and that woody encroachment may sometimes involve a net loss of carbon when changes in soil carbon are included (Jackson *et al*., 2002). Houghton's revised estimate suggests that the sink in trees is only 40% of that observed by forest inventories (Table 4).

Similar conclusions may apply to all of the northern mid-latitudes (Tables 2 and 3). Both forest inventories and inverse calculations with atmospheric data show terrestrial ecosystems to be a significant carbon sink, while changes in land use show a sink near zero. Either analyses of land-use change are incomplete, or other mechanisms besides land management must be responsible for the observed sink, or some combination of both. The fraction of the northern carbon sink attributable to changes in land use and land management remains uncertain. If the US is representative, it might be as high as 98% (Caspersen *et al*., 2000) or as low as 40% (Schimel *et al*., 2000; Houghton, in press).

Distinguishing the roles of regrowth and enhanced growth in the current mid-latitude sink is important. If regrowth is dominant, the current sink may be expected to diminish as forests age (Hurtt *et al*., 2002). If enhanced growth is important, the magnitude of the carbon sink may be expected to increase in the future. Carbon cycle models used to calculate future concentrations of atmospheric CO_2 from emissions scenarios assume the latter (that the current terrestrial sink will increase) (Prentice *et al*., 2001). These calculated concentrations are then used in general circulation models to project future rates of climatic change. If the current terrestrial sink is largely the result of regrowth, rather than enhanced growth, future projections of climate are systematically low. Quantification of the relative roles of regrowth and enhanced growth will require examination of forest age structure over more than two forest inventories and in other regions of the US than Caspersen *et al*. considered; and it will require more complete and spatially detailed assessments of land-use change and land management than Houghton's (in press) spatially-aggregated analyses.

The tropics

How do different methods compare in the tropics? Inverse calculations show that tropical lands are a net source of carbon, $1.2 \pm 1.2\,\mathrm{Pg\,C\,yr^{-1}}$ for the period 1992–1996 (Gurney *et al*., 2002). Accounting for the effects of rivers (Aumont *et al*., 2001) suggests that the net terrestrial source may be 1.5 ($\pm$ 1.2) $\mathrm{Pg\,C\,yr^{-1}}$ (Table 2). Because there are few air-sampling stations over tropical lands, and because atmospheric transport over the tropics is not well understood, the error surrounding estimates of flux based on inverse methods is larger for the tropics than it is for northern mid-latitudes.

Forest inventories for large areas of the tropics are rare, although repeated measurements of permanent plots throughout the tropics suggest that undisturbed tropical forests are accumulating carbon, at least in the neo-tropics (Phillips *et al*., 1998). The number of such plots was too small in tropical African or Asian forests to demonstrate a change in carbon accumulation, but assuming the plots in the neo-tropics were representative of undisturbed forests in that region suggests a sink of 0.62 ($\pm$0.30) $\mathrm{Pg\,C\,yr^{-1}}$ for mature humid neo-tropical forests (Phillips *et al*., 1998). The finding of a net sink has been challenged, however, on the basis of systematic errors in measurement. Clark (2002) notes that many of the measurements of diameter included buttresses and other protuberances, while the allometric regressions used to estimate biomass were based on above-buttress relationships. Furthermore, these stem protuberances display disproportionate rates of radial growth. Finally, some of the plots were on recent floodplains where primary forests accumulate carbon. Phillips *et al*. (2002) counter that the errors are minor, but the results remain contentious.

Thus, the two methods most powerful in constraining the northern net sink (inverse analyses and forest inventories) are weak or lacking in the tropics, and the carbon balance of the tropics is less certain.

Initially, support for an accumulation of carbon in undisturbed tropical forests came from measurements of CO_2 flux by eddy correlation (Grace *et al*., 1995; Malhi *et al*., 1998). Results showed large sinks of carbon in undisturbed forests, that, if scaled up to the entire tropics, yield sinks in the range of 3.9–10.3 $\mathrm{Pg\,C\,yr^{-1}}$ (Malhi *et al*., 2001), much larger than the emissions of carbon from deforestation. Tropical lands seemed to be a net carbon sink. Recent measurements raise doubts about these initial results. The eddy correlation method for measuring CO_2 flux includes both daytime and nighttime measurements. The direction of flux differs day and night, with CO_2 uptake dominating during the day and respiration during the night. Unfortunately, the micrometeorological conditions also differ systematically day and night. Wind speeds are much reduced at night, and the assumption of the eddy flux method that lateral transport is unimportant may not be valid under calm conditions (Miller *et al*., in press). When flux measurements are corrected for calm conditions, the net carbon balance is nearly neutral. One recent study in an old-growth forest in the Tapajós National Forest, Pará, Brazil, shows a small net CO_2 source (Saleska *et al*., in review). The results in that forest are supported by measurements of biomass (forest inventory) (Rice *et al*., in press). Living trees are accumulating carbon, but the decay of downed wood releases more, for a small net source. Both fluxes suggest that the stand is recovering from a disturbance several years earlier.

The recent observation that the rivers and streams of the Amazon are a strong source for CO_2 (Richey *et al*., 2002) may help balance the large sinks measured in some upland sites. The riverine source is included in inverse calculations based on atmospheric data and models and does not change those estimates of a net source (Gurney *et al*., 2002).

The net flux of carbon from land-use change and management in the tropics is clearly a source of carbon to the atmosphere, although the magnitude is uncertain. Based on data from the FAO (2001), Houghton (in press) estimates that the net flux resulting from deforestation, afforestation, and wood harvest in the tropics was a source averaging 2.2 $\mathrm{Pg\,C\,yr^{-1}}$ during the 1990s. Sinks of 0.43 $\mathrm{Pg\,C\,yr^{-1}}$ were calculated for forests recovering from logging activities (Table 5), but these sinks were more than offset by the large emissions from deforestation (and associated burning and decay of organic matter).

The results from different methods allow at least two, mutually exclusive, explanations for the net terrestrial source of carbon from the tropics (Table 2). One suggests that a large release of carbon from land-use change (Houghton, in press; Fearnside, 2000) is partially offset by a large sink in undisturbed forests (Malhi *et al*., 1998; Phillips *et al*., 1998, 2002). The other suggests that the source from deforestation is smaller (see below), and that the net flux from undisturbed forests is nearly zero (Rice *et al*., in press; Saleska *et al*., in review). Under the first explanation, some sort of growth enhancement (or past natural disturbance) is required to explain the large

Table 5 Estimates of the associated sources (+) and sinks (–) of carbon ($Pg\,C\,yr^{-1}$ for the 1990s) from different types of land-use change and management (from Houghton, in press)

Activity	Tropical regions	Temperate and boreal zones	Globe
1. Deforestation	2.110*	0.130	2.240
2. Afforestation	−0.100	−0.080	−0.180
3. Reforestation (agricultural abandonment)	0*	−0.060	−0.060
4. Harvest/management	0.190	0.120	0.310
a. Products	0.200	0.390	0.590
b. Slash	0.420	0.420	0.840
c. Regrowth	−0.430	−0.690	−1.120
5. Fire suppression	0	−0.030	−0.030
6. Non-forests			
a. Agricultural soils	0	0.020	0.020
b. Woody encroachment†	0	−0.060	−0.060
Total	2.200	0.040	2.240

*Only the net effect of shifting cultivation is included. The gross fluxes from repeated clearing of fallow lands and temporary abandonment are not included.
†Probably an underestimate. The estimate is for the US only, and similar values may apply in South America, Australia, and elsewhere.

current sink in undisturbed forests. Under the second, the entire net flux of carbon may be explained by changes in land use, but the source from land-use change is smaller than estimated by Houghton (1999, in press).

A third possibility, that the net tropical source is larger than indicated by inverse calculations (uncertain in the tropics), is constrained by the magnitude of the net sink in northern mid-latitudes. The latitudinal gradient in CO_2 concentrations constrains the difference between the northern sink and tropical source more than it constrains the absolute fluxes. The tropical source can only be larger than indicated by inverse calculations if the northern mid-latitude sink is also larger. As discussed above, the northern mid-latitude sink is thought to be in the range of 1–2.6 $Pg\,C\,yr^{-1}$, but the estimates are based on the assumption that the preindustrial north–south gradient in CO_2 concentrations was zero (similar concentrations at all latitudes). No data exist for the preindustrial north–south gradient in CO_2 concentrations, but following Keeling *et al*. (1989), Tayor & Orr extrapolated the current CO_2 gradient to a zero fossil fuel release and found a negative gradient (lower concentrations in the north). They interpreted this negative gradient as the preindustrial gradient, and their interpretation would suggest a northern sink larger than generally believed. In contrast, Conway & Tans (1999) interpret the extrapolated zero fossil fuel gradient as representing the current sources and sinks of carbon in response to fossil fuel emissions and other human activities, such as present and past land-use change. The current sink in the northern mid-latitudes results, in part, from the fact that ~90% of CO_2 emissions from fossil fuel combustion are in the northern hemisphere. Most investigators of the carbon cycle favor this interpretation.

The high estimates of carbon emissions attributed to land-use change in the tropics (Fearnside, 2000; Houghton, in press) may also be challenged. Potentially, there are at least three reasons why these studies may have overestimated the tropical emissions from land-use change: rates of tropical deforestation may be overestimated, biomass of tropical forests may be overestimated, or rates of decay may be overestimated. The high estimates of a tropical source (Fearnside, 2000; Houghton, in press) are based on rates of deforestation reported by the FAO (2001). The FAO uses expert opinion to determine the rates but must report a country's official governmental estimate if one exists. It is somewhat surprising that the FAO would overestimate rates of deforestation. One can imagine that a country might want to underreport its rates of deforestation to appear environmentally 'correct'. Why would it over-report the rate? Perhaps few countries insist on underreporting rates of deforestation, and the high estimates are rather the result of poor or biased data. The FAO also uses satellite data to monitor changes in forest area (FAO, 2000). However, their 10% sample of tropical forest area may not be adequate to capture the highly clumped distribution of deforestation (Tucker & Townshend, 2000).

Two new studies of tropical deforestation (Achard *et al*., 2002; DeFries *et al*., 2002) report lower rates than the FAO and lower emissions of carbon than Fearnside or Houghton. The study by Achard *et al*. (2002) found rates 23% lower than the FAO for the 1990s (Table 6). Their analysis used high-resolution satellite data over a 6.5% sample of tropical humid forests, stratified by 'deforestation hot-spot areas' defined by experts. In addition to observing 5.8×10^6 ha of outright deforestation in the tropical humid forests, Achard *et al*. also observed

2.3×10^6 ha of degradation. Their estimated carbon flux, including changes in the area of dry forests as well as humid ones, was $0.96\,\mathrm{Pg\,C\,yr^{-1}}$. The estimate is probably low because it did not include the losses of soil carbon that often occur with cultivation or the losses of carbon from degradation (reduction of biomass within forests). Soils and degradation accounted for 12 and 26%, respectively, of Houghton's estimated flux of carbon for tropical Asia and America and would increase the total flux to $1.3\,\mathrm{Pg\,C\,yr^{-1}}$ if the same percentages were applied to the estimate by Archard *et al*.

The second recent estimate of tropical deforestation (DeFries *et al*., 2002) was based on coarse resolution satellite data (8 km), calibrated with high resolution satellite data to identify percentage tree cover and to account for small clearings that would be missed with the coarse resolution data. The results yielded estimates of deforestation that were on average 54% lower than those reported by the FAO (Table 6). According to DeFries *et al.* the estimated net flux of carbon for the 1990s was 0.9 (range 0.5–1.4) $\mathrm{Pg\,C\,yr^{-1}}$.

If the tropical deforestation rates obtained by Archard *et al*. and DeFries *et al*. were similar, there could be little doubt that the FAO estimates are high. However, the estimates are as different from each other as they are from those of the FAO (Table 6). Absolute differences between the two studies are difficult to evaluate because Achard *et al*. considered only humid tropical forests, while DeFries *et al*. considered all tropical forests. The greatest differences are in tropical Africa, where the percent tree cover mapped by DeFries *et al*. is most unreliable because of the large areas of savanna. Both studies suggest that the FAO estimates of tropical deforestation are high, but the rates are still in question. The tropical emissions of carbon estimated by the two studies (after adjustments for degradation and soils) are about half of Houghton's estimate: 1.3 and $0.9\,\mathrm{Pg\,C\,yr^{-1}}$, as opposed to $2.2\,\mathrm{Pg\,C\,yr^{-1}}$ (Table 5). If the rates of deforestation reported by FAO are high, Houghton's estimate of a tropical source is also high, by about the same proportion.

Estimates of a tropical source of carbon will also be high if estimates of tropical forest biomass are high. The biomass of tropical forests, particularly those forests that are being deforested or degraded, is poorly known (Houghton *et al*., 2000, 2001). Furthermore, logging, shifting cultivation, and other uses of forests are reducing the biomass of tropical forests. These processes of degradation may reduce the amount of carbon emitted through deforestation, but the process of degradation releases carbon as well, so the total loss of carbon is the same (with more coming from degradation and less from deforestation).

Finally, if downed trees take longer to decay and/or regrowth of biomass is faster than generally assumed, the calculated emissions from logging and deforestation may be overestimated (Monastersky, 1999), especially in regions, such as Amazonia, where rates of logging have been increasing. In regions with a longer history of logging and deforestation, using higher or lower rates of decay does not significantly change the calculated flux for the 1990s.

Table 6 Annual rate of change in forest area* for the 1990s

Tropical humid forests			
	FAO (2001) $10^6\,\mathrm{ha\,yr^{-1}}$	Achard *et al*. (2002) $10^6\,\mathrm{ha\,yr^{-1}}$	Achard *et al*. (2002) % lower than FAO
Tropical America	2.7	2.2	18
Tropical Asia	2.5	2.0	20
Tropical Africa	1.2	0.7	42
All tropics	6.4	4.9	23
		DeFries *et al*. (2002)	
All tropical forests	FAO (2001) $10^6\,\mathrm{ha\,yr^{-1}}$	$10^6\,\mathrm{ha\,yr^{-1}}$	% lower than FAO
Tropical America	4.4	3.179	28
Tropical Asia	2.4	2.008	16
Tropical Africa	5.2	0.376	93
All tropics	12.0	5.563	54

*The net change in forest area is not the rate of deforestation but, rather, the rate of deforestation minus the rate of afforestation.

Conclusions

In both the northern mid-latitudes and the tropics the terrestrial sinks obtained through inverse calculations with atmospheric data are larger (or the sources smaller) than those obtained from bottom-up analyses (land-use change and forest inventories). Is there a bias in the atmospheric analyses? Or are there sinks not included in the bottom-up analyses?

For the northern mid-latitudes, when estimates of change in nonforests (poorly known) are added to the results of forest inventories, the net sink barely overlaps with estimates determined from inverse calculations. Changes in land use yield smaller estimates of a sink. It is not clear how much of the discrepancy is the result of omissions of management practices and natural disturbances from analyses of land-use change, and how much is the result of environmentally enhanced rates of tree growth. In other words, how much of the carbon sink in forests can be explained by age structure (i.e. previous disturbances and management), and how much by enhanced rates of carbon storage? The question is important for predicting future concentrations of atmospheric CO_2.

In the tropics, the uncertainties are similar but also greater because inverse calculations are more poorly constrained and because forest inventories are lacking. Existing evidence suggests two possibilities. Either large emissions of carbon from land-use change are somewhat offset by large carbon sinks in undisturbed forests, or lower releases of carbon from land-use change explain the entire net terrestrial flux, with essentially no requirement for an additional sink. The first alternative (large sources and large sinks) is most consistent with the argument that factors other than land-use change or management are responsible for observed carbon sinks (i.e. enhanced rates of growth). The second alternative is most consistent with the findings of Caspersen *et al.* (2000) that there is little enhanced growth. Overall, in both northern and tropical regions changes in land use exert a dominant influence on the flux of carbon, and it is unclear whether other factors have been important in either region. These conclusions question the assumption used in predictions of future climatic change that the current terrestrial carbon sink will increase.

A resolution of the regrowth – enhanced growth question could be obtained in northern latitudes with analysis of tree growth rates over multiple inventories and with a better documentation of historical and current changes in land use, including the spatial extent of woody encroachment. In the tropics the greatest reduction in the uncertainty of carbon flux estimates would result from a systematic and spatial determination of rates of deforestation and afforestation, and to a lesser extent, biomass. The current lack of an adequate monitoring program to measure changes in forest cover in the tropics is remarkable. Such a monitoring program, using high-resolution satellite data over the last three decades and into the future, would probably do more to constrain the tropical and global net terrestrial flux of carbon than any other measurement.

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