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The Effects of Land Use and Management on the Global Carbon Cycle

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Abstract

Major uncertainties in the global carbon (C) balance and in projections of atmospheric CO_2 include the magnitude of the net flux of C between the atmosphere and land and the mechanisms responsible for that flux. A number of approaches, both top-down and bottom-up, have been used to estimate the net terrestrial C flux, but they generally fail to distinguish possible mechanisms. In contrast, calculations of C-fluxes based on land-use statistics yield both an estimate of flux and its attribution, that is, land-use change. A comparison of the flux calculated from land-use change with estimates of the changes in terrestrial C storage defines a residual terrestrial C sink flux of up to 3 PgC yr^{-1}, usually attributed to the enhancement of growth through environmental changes (for example, CO_2 fertilization, increased availability of N, climatic change). We explore whether management (generally not considered in analyses of land-use change), instead of environmental changes, might account for the residual sink flux. We are unable to answer the question definitively. Large uncertainties in estimates of terrestrial C fluxes from top-down analyses and land-use statistics prevent any firm conclusion for the tropics. Changes in land use alone might explain the entire terrestrial sink if changes in management practices, not considered in analyses of land-use change, have created a sink in the northern mid-latitudes.

Introduction

Several lines of evidence suggest that terrestrial ecosystems have been a net sink for carbon (C) in recent years. The evidence is more compelling for northern mid-latitude lands than it is for the tropics, but a number of analyses suggest a terrestrial C sink in the tropics as well. The mechanisms thought to be responsible for the terrestrial sink have included factors that enhance growth, such as CO_2 fertilization, nitrogen deposition, and the differential effects of climate variability on photosynthesis and growth relative to respiration and decay. Changes in land use may also lead to terrestrial C sinks through the regrowth of forests following agricultural abandonment or harvest, but the net effect of land-use change is estimated to have released C globally and, thus, does not explain the net terrestrial sink. The recent analysis by Caspersen et al. (2000) suggests that 98% of the C accumulation in trees in five eastern U.S. states can be explained by the age structure of the forests (that is, regrowth), and only 2% may be attributed to enhanced growth. If environmental growth enhancement were negligible, it would have important implications for the future of the terrestrial C-sink. We explore in this paper whether the results from analyses of land-use change are consistent with other observationally-based estimates of the terrestrial C fluxes. The review is similar to a recent comparison of methods used to estimate terrestrial sources and sinks of C (House et al., in press), but the emphasis here is on changes in land use.

Methods for Evaluation the Terrestrial Flux of Carbon

Both top-down approaches based on atmospheric observations and bottom-up approaches based on terrestrial data have been used to estimate C-fluxes between terrestrial ecosystems and the atmosphere. In global top-down approaches, a basic assumption is that the change in atmospheric, oceanic and terrestrial C storage equals fossil C emissions. Fossil emissions are known from trade statistics (Marland et al., 2000) and the atmospheric change from direct atmospheric measurements or from ice core data. The partitioning between the terrestrial and oceanic sink is determined from additional information, such as the observed trend in atmospheric O_2 or $^{13}CO_2$. The global budget equations for atmospheric CO_2 and O_2 (Keeling et al., 1996, Battle et al., 2000) or for CO_2 and $^{13}CO_2$ (Keeling et al., 2001, Joos and Bruno, 1998) are solved for changes in terrestrial and oceanic C storage. The recent IPCC assessment (Prentice et al. 2001) reported an average net sink during the 1990s of 1.4 ($\pm$0.7) PgC yr^{-1} for the world's terrestrial ecosystems. In other global methods, the oceanic sink is estimated from oceanic tracer distributions (Quay et al., 1992, Heimann and Meier-Reimer, 1996, Gruber and Keeling, 2001, Takahashi et al., 2002, McNeil et al, 2003) or by applying an ocean model (Siegenthaler and Oeschger, 1987, Bruno and Joos, 1997). Then, the change in terrestrial storage is calculated by difference from the atmospheric C balance.

In a second top-down approach, regional surface C fluxes are estimated from the observed spatial gradients in the atmospheric concentrations of CO_2 (sometimes including the distribution of $^{13}CO_2$ and global O_2 as well) in combination with an atmospheric transport model (Rayner et al, 1999, Guerney et al., 2002, Bousquet et al, 2000). Results of this regional inverse approach depend on the transport model and the way boundary conditions are prescribed (Guerney et al. 2002). Globally, the world's terrestrial regions summed to a net sink of 1.4 ($\pm$0.8) PgC yr^{-1} for the period 1992-1996 (Gurney et al. 2002), identical to the average obtained from global approaches (Prentice et al. 2001).

An important distinction exists between global and regional inverse approaches. In the global top-down approaches, changes in C *storage*, that is in the oceanic and terrestrial C sink, are calculated. In contrast, the regional inverse method yields C-*fluxes* between the land or ocean surface and the atmosphere. These C-fluxes include both natural and anthropogenic components. Horizontal exchange between regions must be taken into account to estimate regional and global changes in oceanic and terrestrial storage For example, the fluxes will not accurately reflect changes in the amount of C on land or in the sea if some of the C fixed by terrestrial plants is transported by rivers to the ocean and respired there (Sarmiento and Sundquist, 1992, Tans et al., 1995, Aumont et al., 2001).

Bottom-up approaches include data from forest inventories (Goodale et al., 2002) and analyses of land-use change (Houghton,in press). Forest inventories provide systematic measurement of wood volumes from more than a million plots throughout the temperate and boreal zones. Converting volumes to total biomass and accounting for the fate of harvested products and changes in the pools of woody debris, forest floor, and soils yield C budgets for the forests of northern mid-latitudes. A net sink of 0.6-0.7 PgC yr^{-1} was recently reported for the northern mid-latitude forests (Goodale et al. 2002). Unfortunately, forest inventories are rare over large regions of the tropics, and similar comparisons are not possible there. However, long-term measurements on a small number of permanent plots in tropical forests suggest that undisturbed forests may be functioning as a large C sink (Phillips et al. 1998). This result is discussed in more detail below.

A second bottom-up approach estimates the flux of C associated with changes in land use. These analyses are based on rates of land-use change and the changes in C storage (in living and dead vegetation, soils, and wood products) that accompany a change in land use. The net effect of deforestation, reforestation, cultivation, and logging is calculated to have released an average of 2.0 PgC yr^{-1} globally during the 1980s, and 2.2 PgC yr^{-1} during the 1990s (Houghton, in press). The approach does not consider all lands, but only those that have been cleared, cultivated, planted, logged, and, in some analyses, burned. The calculated fluxes include the C sinks associated with forest (re)growth as well as the sources from burning and decay of organic matter.

Do changes in land use explain net terrestrial sources and sinks of carbon?

The *source* of C from land-use change, compared to the net *sink* found by other analyses, suggests that other factors are important for explaining the sink. However, most of the sink estimates need adjustments to make them comparable. Furthermore, a number of recent analyses have modified estimates of the magnitude of the terrestrial flux. In this paper we review these new estimates from the perspective of land-use change. In particular, do changes in land use and land management account for the entire change in C storage in terrestrial ecosystems? Or do other factors contribute significantly to a terrestrial sink?

The current (1990s) global carbon balance

According to the latest IPCC assessment, terrestrial ecosystems, globally, were a net sink for C, averaging 0.2 ($\pm$0.7) PgC yr^{-1} in the 1980s and 1.4 ($\pm$0.7) PgC yr^{-1} for the 1990s (Prentice et al. 2001). The reason for the large increase between the 1980s and 1990s is unknown. Also unexplained is the apparent decrease in the net oceanic C 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, not less, C. The partitioning of the C sink between land and ocean was based on recent atmospheric CO_2 and O_2 data and included a small correction for the outgassing of O_2 from the oceans (Prentice et al. 2001).

More recent analyses (Bopp et al., 2002, Keeling and Garcia, 2002, Plattner et al.,2002) determined that the outgassing of O_2 was much larger than estimated by Prentice et al. (2001). The recalculated partitioning of C uptake between land and sea (Table 1) by Plattner et al. (2002) shows a larger oceanic uptake in the 1990s than the

1980s, in line with results of oceanic models. The terrestrial uptake is more similar between decades than estimated by Prentice et al. (2001) (an average difference of 0.3, rather than 1.2, PgC yr^{-1}). The net terrestrial flux averaged 0.4 and 0.7 PgC yr^{-1} during the 1980s and 1990s, respectively.

Estimates of a global net C flux from the atmosphere to the land, calculated by summing regional fluxes, which, in turn, are obtained by inverting the spatial CO_2 distribution, average around 1.4 PgC yr^{-1} (Gurney et al. 2002), higher than that obtained from changes in O_2 and CO_2 (0.7 PgC yr^{-1}). However, these estimates of flux need to adjusted for riverine transport to obtain an estimate of the terrestrial C sink. Several studies have tried to adjust atmospherically-based C fluxes to account for this transport of C by rivers. Sarmiento and Sundquist (1992) estimated a pre-industrial net export by rivers of 0.4-0.7 PgC yr^{-1}, balanced by a net terrestrial uptake of C through photosynthesis and weathering. Aumont et al (2001) estimated a terrestrial uptake due to continental weathering of 0.7 PgC yr^{-1}. Reducing the net terrestrial sink obtained through inverse calculations (1.4 PgC yr^{-1}) by 0.6 PgC yr^{-1} yields a result of 0.8 PgC yr^{-1}, overlapping with the estimate obtained though changes in O_2 and CO_2 concentrations (Table 2). The two methods based on atmospheric measurements yield similar global estimates of a small net terrestrial C sink. The source of 2.2 PgC yr^{-1} calculated from changes in land use is very different from this global net terrestrial sink (0.7 PgC yr^{-1}).

A residual (terrestrial) flux of carbon

If the net terrestrial flux of C during the 1990s was 0.7 PgC yr^{-1}, and 2.2 PgC yr^{-1} were emitted as a result of changes in land use, then 2.9 PgC 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 called the "missing sink"). The C released from land-use change and the residual sink sum to the observed net sink. To the extent that the residual terrestrial sink exists at all suggests that processes other than land-use change are affecting C storage on land. On the other hand, the residual sink is calculated by difference; if the emissions from land-use change are overestimated, the residual sink will also be high.

A longer-term estimate of the residual terrestrial C flux suggests that it was nearly zero before 1935 (Fig. 1). That is, changes in land use explained most of the net terrestrial C flux until about 1935. Since that time the residual terrestrial sink has generally increased (Bruno and Joos, 1997).

This residual terrestrial sink may result from bias in the methods. For example, limited quantitative understanding of the processes regulating oceanic O_2 outgassing may introduce biases in global sink estimates. It is difficult to simulate correctly the contribution of the seasonal biosphere-atmosphere exchange to the observed atmospheric CO_2 field ('rectifier effect') (Denning et al., 1995) as required in atmospheric transport inversions. The contribution of fluxes associated with the natural C cycle to spatial gradients is debated (Taylor and Orr, 2000). Nevertheless, most inverse analyses yield higher terrestrial C sinks than bottom-up, land-based approaches. The resulting residual C sink has traditionally been attributed to environmental changes.

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

C resulting directly from human activity (conversion and modification of terrestrial ecosystems). There may be other sources and sinks of C not related to land-use change (such as sinks caused by CO_2 fertilization) that exchange C with the atmosphere and are captured by other methods, but that are ignored in analyses of land-use change.

A number of process-based terrestrial carbon models simulate the effects of CO_2, N, and climate on carbon storage (the effects commonly thought to account for the residual terrestrial flux). Examples include the four models described in a recent analysis by McGuire et al. (2001). Each of the models included some changes in land use as well as the effects of CO_2 and climate on terrestrial C storage. Although the models are very different from the bookkeeping model used by Houghton (in press), the analysis by McGuire et al. is nearly the complement of Houghton's analysis: it includes environmental effects, while Houghton's analysis does not; it does not consider changes in pastures, shifting cultivation, or logging, while Houghton's analysis does (Table 3). Thus, the two studies, together, appear to address both the flux of C from land-use change and the residual terrestrial flux. However, although process-based models generally find a global terrestrial C sink consistent with the magnitude of the residual terrestrial sink, the models are difficult to validate. Field observations of carbon sinks do not indicate the mechanism(s) responsible, and the relative importance of different growth-enhancing mechanisms varies among models. It is possible that much of the terrestrial sink attributed to environmental factors is, rather, the result of errors or omissions in analyses of land-use change, a possibility explored below.

The only aspect of the studies (McGuire et al. and Houghton) that is redundant is the flux attributable to changes in the area of croplands. The difference in cropland fluxes (0.8 vs. 1.2 PgC yr^{-1}) (Table 3) is at least partly related to the manner in which the studies accounted for the expansion of croplands in the tropics (see the recent paper by House et al. (in press) for other differences). McGuire et al. used net changes in cropland area (from Ramankutty and Foley 1999) to determine annual rates of clearing. Houghton (in press) used rates of clearing based on changes in forest area reported by the FAO (2001). The net reduction in forest area often exceeded the increase in agricultural (cropland and pasture) area, and Houghton assumed that the excess deforestation resulted from simultaneous clearing (deforestation) and abandonment of croplands. That is, forests were cleared for new croplands, yet the area in croplands did not change correspondingly because croplands were also abandoned. The abandoned croplands were not reported as returning to forest (such lands often become degraded), and thus the loss of forest area exceeded the increase in cropland. Because more forests were cleared for croplands under Houghton's assumption than under McGuire's assumption, the flux of C attributed to cropland expansion and abandonment was greater in Houghton's analysis.

The difference in approaches points to the importance of accounting for all changes in land use. The area in croplands, and to a lesser extent, pastures and forests are often documented. Degraded lands are not. Thus, one can construct patterns of land-use change from agricultural statistics that miss important changes in C. Whether the sources and sinks are attributed to croplands or to degradation is of secondary importance. The important point is to capture the major changes in C (i.e., forests). Analyses based on satellite data rather than on agricultural statistics have the potential for full land-use accounting (Defries et al. 2002).

In summary, available bottom-up and top-down analyses, despite existing uncertainties, suggest a global net terrestrial sink, and a residual terrestrial sink. This conclusion is also supported by estimates of oceanic C uptake based on oceanic tracer data or models that are not explicitly discussed here (Prentice et al., 2001). Additional comparisons of terrestrial C fluxes can be obtained from a consideration of tropical and extra-tropical regions separately.

The northern mid-latitudes

The net terrestrial C sink of ~0.7 PgC yr^{-1} for the 1990s is not evenly distributed over the land surface. Almost all analyses indicate that northern mid-latitude lands were a net sink, while tropical lands were a net source. As long as the north-south gradient in CO_2 concentrations was the only constraint, the difference between the northern sink and the tropical source was defined, but the individual values were not (Tans et al. 1990). Thus, a sink of 2 PgC yr^{-1} in northern mid-latitudes and a source of 0 PgC yr^{-1} in the tropics could not be distinguished from a northern sink of 5 PgC yr^{-1} and a tropical source of 3 PgC yr^{-1}. Based on an enlarged CO_2 monitoring network, the sink in northern mid-latitudes for the 1990s is now thought to be 2.4 PgC yr^{-1} (Gurney et al. 2002) (not accounting for the riverine flux), which is offset to some degree by a net tropical source of 1.2 PgC yr^{-1}. It has been estimated that rivers transport around 0.3 PgC yr^{-1} from the land to the ocean in the northern mid and high latitudes. Subtracting this riverine transport from the terrestrial net C-flux of 2.4 PgC yr^{-1} yields a northern terrestrial sink of 2.1 PgC yr^{-1}

One analysis of the distribution of atmospheric CO_2 concentrations, without use of a transport model, suggests that much of the current terrestrial flux in northern extratropical regions is part of a natural circulation of C; and when the natural CO_2 gradients are accounted for in transport inversion, the current (perturbation) sink is much smaller (<0.5 PgC yr^{-1}) (Taylor and Orr 2000) than suggested by others (Gurney et al., 2002) (see Conway and Tans (1999) for an alternative interpretation). A resolution of these estimates is beyond the scope of this analysis.

A recent synthesis of data from forest inventories found a net terrestrial sink of 0.7 PgC yr^{-1} for the northern mid-latitudes (Goodale et al. 2002). The estimate is less than half the sink for all northern mid-latitude lands inferred from atmospheric data, but if non-forest ecosystems throughout the region are as important in storing C as they seem to be in the U.S. (see below), this bottom-up analyses yields a sink (~1.4 PgC yr^{-1}) that is closer to the top-down estimate (2.1 PgC yr^{-1}). Pacala et al. (2001) reported a similar overlap of top-down and bottom-up estimates for the U.S. Admittedly, the sink in non-forests is very uncertain. On the other hand, the northern sink of 2.1 PgC yr^{-1} from Gurney et al. is for 1992-1996 and would probably have been lower if averaged over the entire decade (see other estimates in Prentice et al. 2001). Top-down estimates for a short time period are sensitive to large interannual variations in the growth rate of atmospheric CO_2. Another reason for potential discrepancies is that only C in trees is monitored in forest inventories, whereas changes in soil C may be equally or more important. On the other hand, the few field investigations that have considered soil C have found that soils account for only a small fraction (5-15%) of the ecosystem's C sink (Gaudinski et al. 2000, Barford et al. 2001).

Estimates of C-fluxes based on land use change statistics are around zero in the northern extratropical region (Houghton, in press). Taken at face value, this suggests that processes other than land-use change are responsible for a northern sink of 1 to 2 PgC yr^{-1}. Next, we compare different bottom-up estimates available for the contiguous United States to investigate the plausibility of the estimate by Houghton.

The United States

Top-down estimates for relatively small regions such as the US are currently not very reliable. Gurney et al, 2002 estimate a C flux from the atmosphere to the land of 0.85 ± 0.5 Pg C yr^{-1} for the US. Based on an analysis of changes in land use, Houghton et al. (1999) estimated a C sink of 0.15 – 0.35 PgC yr^{-1} attributable to changes in land use. Pacala et al. (2000) revised the estimate upwards by including additional processes, but in so doing, they included sinks not necessarily resulting from land-use change. Their estimate for the uptake of C by forests, for example, was the uptake measured by forest inventories. If all of the accumulation of C in U.S. forests were the result of recovery from past land-use changes, then the uptake estimated from forest inventories should equal the flux estimated from land-use change statistics. The study by Caspersen et al. (2000) suggests that such an attribution is warranted. However, the analysis by Houghton et al. (1999) found that past changes in land use could account for only 10-30% of the observed C accumulation in trees. The uptake calculated for forests recovering from agricultural abandonment, fire suppression, and earlier harvests was only 10-30% of the uptake measured by forest inventories. The contributions reach 65% if the uptake Houghton et al. attributed to woodland 'thickening' (0.52 PgC yr^{-1}) is included (Table 4). The results appear to be inconsistent with those of Caspersen et al. (2000).

The work of Caspersen et al. (2000) has been criticized by Joos et al. (2002) in two important respects. First, 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. Enhancements of even 0.1% per year yield estimates of biomass indistinguishable from those observed. Second, even a small enhancement of 0.1% per year in net primary production would, for a doubling of CO_2, yield a 25% increase in growth (e.g., McGuire et al. (2001) in Table 3). Thus a small enhancement of growth may, nevertheless, translate into a significant C sink (Joos et al. 2002). Regrowth is clearly the dominant process in forests recovering from a disturbance, but C uptake by regrowth may be offset by C loss due to disturbances elsewhere (or at a later time). Hence, relatively small growth enhancement fluxes may play an important role for the net change in terrestrial C storage when considering large spatial areas and temporal scales longer than a few years. The question becomes: What is the current balance between C accumulation in regrowing forest versus the loss due to disturbances such as fire, storms, insects and how does growth enhancement affect this balance. Answering the question will be difficult, but one way to answer it is through the reconstruction of past human-induced and natural disturbances for the contiguous US and other regions of the globe.

Houghton et al. (1999) and Houghton (in press) may have underestimated the sink attributable to land-use change. Houghton did not consider forest management practices other than harvest (including regrowth) and fire suppression. Such activities as weed control, fertilization, breeding programs, and thinning have increased the productivity of US forests but were not accounted for. Neither did Houghton consider the proliferation of trees in suburban areas, or natural disturbances, which in boreal forests are more important than logging in determining the current age structure and, hence, rate of C accumulation in forests (Kurz and Apps 1999). A fourth 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 C sink in U.S. lands 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 non-forest ecosystems could account for a significant C sink. From 36-43% of the net sink estimated by Pacala et al. and about 74% of that estimated by Houghton et al. was in non-forests. Initially, Houghton et al. (1999) reported a sink of 0.14 PgC yr^{-1} in agricultural soils, an upper limit of 0.12 PgC yr^{-1} in woody vegetation expansion or encroachment, and an upper limit of 0.05 PgC yr^{-1} in the thickening of woodlands. However, subsequent analyses of C accumulation resulting from conservation tillage in agricultural soils indicate a smaller sink (Schimel et al. 2000, Pacala et al. 2001). Furthermore, a more conservative estimate for woody encroachment and woodland thickening is half of the original upper limit proposed by Houghton et al. (1999). The reasons for the lower estimate are several fold. First, loss (rather than gain) of woody plants is occurring in some systems (Billings 1990). Second, a recent study of woody encroachment suggests that when changes in soil C are included, the displacement of grasses with woody shrubs may actually involve a net loss of C (Jackson et al., 2002), although this result remains highly contentious (Asner et al. in review). Somewhat independent of the belowground (soil organic C) responses to woody encroachment, the largest area of woody encroachment studied (> 40,000 ha in Texas) indicates an increase in aboveground C stocks of 0.02 Mg ha^{-1} y^{-1}, accounting for both encroachment and management efforts to remove woody plants (Asner et al. in press). Extrapolated to an the southwest U.S. region represented by this study (~ 50M ha), the results of Asner et al. suggest a net C sink from woody encroachment of about 0.001 PgC yr^{-1}. Finally, a study of pine thickening in Colorado suggested that accumulation rates used by Houghton et al. may be too high (Hicke et al. in review).

Based on this and other emerging evidence, the 'best estimate' for the effects of land-use change (and fire management) on U.S. C storage is thus 0.11 PgC yr^{-1} (Houghton, in press). About 50% of this revised sink for the U.S. is attributable to changes outside of forests. Further, the sink in trees is only 40% of that estimated from forest inventories (Table 4). Thus, changes in land use yield a significantly lower sink than inferred from either inverse calculations or forest inventories. Either an enhancement in growth is equally important, Houghton's analyses of land-use change have omitted some important management or disturbance processes, or the estimates from forest inventories and inverse calculations are too high.

This conclusion probably applies to all of the northern mid-latitudes. Both forest inventories and inverse calculations with atmospheric data show terrestrial ecosystems to be a significant C sink, while analyses of changes in land use show a net sink close to zero. The fraction of the northern C sink attributable to changes in land use and land management remains uncertain (Spiecker et al. 1996). It might be as high as 98% (Caspersen et al. 2000) or as low as 40% (Houghton, in press; Schimel et al. 2000). Resolution will require examination of forest age structure over more than two points in time and in regions other than those considered by Caspersen et al.; or it will require a more complete and spatially-detailed assessment of land-use change and land management in the U.S. and elsewhere. In any case, the impact of past human induced and natural disturbances on the evolution of terrestrial C storage needs to be investigated more carefully.

The Tropics

Do changes in tropical land use account for the net flux of C in that region? Inverse calculations show that tropical lands release on average a flux of 1.2 PgC yr^{-1} during the period 1992-1996 (Gurney et al. 2002). Accounting for a riverine transport of 0.3 PgC yr^{-1} (Aumont et al. 2001) yields a rate of decrease in terrestrial storage of 1.5 PgC yr^{-1}. Because there are few air sampling stations over tropical lands, and because atmospheric transport over the tropics is not well understood, the error surrounding the flux estimate for the tropics is larger than it is for northern mid-latitudes.

A recent study by Townsend et al. (2002) combined atmospheric $^{13}CO_2$ observations, modeling and land-cover change data to investigate pan-tropical C sources and sinks. Their analysis recognizes that deforestation in the tropics has led to an increase in the extent of C_4 plants (warm climate grasses) relative to C_3 plants (woody vegetation such as trees). Because C_3 plants discriminate more strongly against ^{13}C than do C_4 plants, the latter leaves an atmospheric ^{13}C signature more similar to that of the air-sea transfer of CO_2 than to the land-air transfer (Rundel et al. 1989, Ciais et al. 1995). After accounting for the time-integrated replacement of ^{13}C-rich organic matter in forest soils with ^{13}C-poor organic matter in pasture soils (from C_4 plant detritus), or "land-use disequilibrium", Townsend et al. (2002) found that tropical regions were nearly C-neutral.

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 C, 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 C storage, but assuming the plots in the neo-tropics were representative of forests not disturbed by direct human interventions throughout the region yields a sink of 0.62 PgC yr^{-1}. The finding of a net sink for the Amazon, however, has been challenged on the basis on systematic errors in measurement and plot size (Clark 2002; Keller et al. 2002). Phillips et al. (2002) counter that the errors are minor, but the results remain contentious. In sum, the two methods most powerful in constraining the northern net sink are weak or lacking in the tropics, and the C balance of the tropics is less certain.

Support for an accumulation of C in undisturbed tropical forests comes from some of the studies that have measured CO_2 flux by eddy correlation (Grace et al. 1995; Malhi et al. 1998). Some studies suggest that the sinks in forests not disturbed by direct human interventions, if scaled up to the entire region, are larger than the emissions of C from deforestation (Malhi et al. 1998). Tropical lands would thus be a net C sink, but these results are controversial. The eddy correlation method for measuring CO_2 flux includes both daytime and nighttime measurements. The direction of flux differs day and night and the micrometeorological conditions also differ systematically day and night. Wind speeds are much reduced at night, and CO_2 efflux is negatively related to windspeed. If only those nights with the highest wind speeds are used to calculate an annual net flux, estimates change from a net sink to a net source of C (Miller et al., in press). Thus, large sinks in undisturbed forests are suspect. Some recent measurements of CO_2 flux as well as measurements of biomass (forest inventory) do not show a large net sink (Rice et al., in press). In the Tapajós National Forest, Pará, Brazil, living trees were accumulating C, but the decay of downed wood released more C, resulting in a small net source from the site. The results suggest that the stand is recovering from a disturbance several years earlier (Rice et al, in press, Keller et al. in review).

The net flux of C calculated from land-use change in the tropics is clearly a source of C to the atmosphere. Rates of deforestation are larger than rates of afforestation (FAO 2001). Based on data from the FAO, Houghton (in press) estimates that the net C flux resulting from deforestation, afforestation, and wood harvest in the tropics was a net source, averaging 2.2 PgC yr^{-1} during the 1990s. A sink of 0.43 PgC yr^{-1} was calculated for forests recovering from logging activities (Table 5), but this sink was more than offset by the large emissions from deforestation (and associated burning and decay of organic matter).

Comparing the results of different methods shows that the inverse calculations based on atmospheric data and models give a lower net C source from the tropics, just as they give a higher net sink in northern latitudes. In both regions, the sinks obtained through inverse calculations are larger than they are from analyses of land-use change. As discussed above, it is possible that much of the C released from land-use change is balanced by C sinks in forests not disturbed by direct human interventions. The sink (if it exists at all) might be the result of enhanced rates of growth, perhaps from CO_2 fertilization, new inputs of nitrogen, or climatic variation. Alternatively, undisturbed forests are neutral with respect to C, and the source from deforestation is lower than Houghton estimates.

The existing data allow at least two, mutually exclusive explanations for the net tropical flux of C. One suggests that a large release of C from land-use change is partially offset by a large sink in undisturbed forests. The other suggests that the source from deforestation is smaller, and that the net flux from undisturbed forests is essentially zero. Under the first explanation, a growth enhancement (or past natural disturbance) is required to explain the large current sink in undisturbed tropical forests. Under the second, the entire net flux of C may be explained by changes in land use.

A third possibility, that the net tropical C 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. As mentioned above, the latitudinal gradient in CO_2 concentrations constrains the difference between the northern sink and tropical source more than it constrains the absolute fluxes. Thus, the northern sink limits the magnitude of the net tropical source.

In summary, the evidence for a large C sink in the tropics (offsetting the source from land-use change) includes the uptake of C measured by eddy correlation techniques in undisturbed forests (Malhi et al. 1998) and the C accumulation observed on permanent plots in South America (Phillips et al. 1998, 2002). Evidence against a large sink in undisturbed forests includes biases in the measurements of CO_2 flux at many sites (Miller et al., in press; Rice et al., in press) and biases in measurement of change in biomass (Clark 2002). Next, we address potential biases in estimates of the land-use change flux.

Potential Biases in the Tropical Deforestation Source

The high estimates of C emissions attributed to land-use change in the tropics (Fearnside 2000; Houghton, in press) may be too high. Potentially, there are at least three reasons: deforestation rates, tropical forest biomass, and rates of decay may each be overestimated. The rates of deforestation and afforestation used by Houghton (in press) to calculate a net flux are those reported by the FAO. 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.

Two new studies of tropical deforestation, based on satellite data, report lower rates than the FAO and lower emissions of C than Houghton (in press). 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 yr^{-1} of outright deforestation in the tropical humid forests, Achard et al. also observed 2.3×10^6 ha yr^{-1} of degradation. Their estimated C flux, including changes in the area of dry forests as well as humid ones, was 0.96 PgC yr^{-1}. The estimate is probably low because it did not include the losses of C from soils that often occur with cultivation or the losses of C from the degradation observed. Soils and land degradation (reductions of biomass within forests) accounted for 12 and 26%, respectively, of Houghton's estimated flux for tropical Asia and America, and would yield a total flux of 1.3 PgC yr^{-1} if the same percentages were applied to the estimate by Archard et al. (2002).

The second estimate of tropical deforestation (DeFries et al. 2002) was based on coarse resolution satellite data (8km), calibrated with high resolution satellite data to identify % 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 54% less than those reported by the FAO (Table 6). According to DeFries et al., the estimated net flux of C for the 1990s was 0.9 ± 0.4 PgC 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). 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. On the other hand, the results may vary because the studies include different types of forests. Achard et al. considered only humid tropical forests; DeFries included all tropical forests. Both studies suggest that the FAO estimates of tropical deforestation are high, but the rates are still in question. The tropical emissions of C estimated by the two studies are about half of

Houghton's estimate: 1.3 and 0.9 PgC yr^{-1}, as opposed to 2.2 PgC yr^{-1}. Houghton's estimate would be similar if based on these recent estimates of deforestation, lower than the FAO's.

Fearnside's (2000) and Houghton's (in press) estimates of a tropical C source would also be high if their estimates of tropical forest biomass were too 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 and releasing C in the process (Brown et al. 1994, Flint and Richards 1994). These processes of degradation may reduce the amount of C emitted through deforestation, but the loss of C is the same (with more coming from degradation rather than from deforestation).

Finally, if downed trees take longer to decay and/or regrowth of biomass is faster than Houghton 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.

The major uncertainties in the tropics could be reduced with a systematic and spatial determination of rates of deforestation and afforestation, and with a systematic and spatial determination of biomass. In fact, a sensitive measure of biomass from space might help distinguish the changes in C attributable to land-use change from the changes attributable to enhanced growth --- at least for the aboveground biomass component. Measurement of changes in the amount of downed dead wood and soil C will require extensive ground measurements or a combination of ground samples and modeling (Chambers 2000; Keller et al., in press and in review).

Conclusions

There is a large body of evidence for a considerable global net terrestrial C sink. On the other hand, land use change analyses suggest a large global C source, implying an even larger (residual) C sink, more than offsetting the land-use source.

In both the northern mid-latitudes and the tropics the terrestrial C 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 non-forests (poorly known) are added to the results of forest inventories, the result overlaps estimates determined from inverse calculations. Changes in land use include non-forest ecosystems but yield a smaller estimate of a sink. It is not clear whether management practices and natural disturbances, generally lacking in analyses of land-use change, are responsible for an additional sink, or whether environmentally enhanced rates of tree growth are responsible for the difference. Can the C sink in forests be explained by age structure alone (i.e., previous disturbances and management) (Caspersen et al. 2000), or are enhanced rates of C storage important (Houghton et al. 1999, Schimel et al. 2000)?

In the tropics, the uncertainties are similar but also greater because atmospheric data for inverse calculations are more poorly distributed, and because forest inventories are lacking. Alternative approaches yield conflicting results concerning the enhancement of growth (or C storage) in undisturbed forests. Existing evidence suggests two possibilities. Either large emissions of C from land-use change are somewhat offset by large C sinks in undisturbed forests, or lower releases of C 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 C sinks. The second alternative is most consistent with little or no enhanced growth. In both northern and tropical regions changes in land use exert a large influence on the flux of C. It is unclear whether other factors have been important. Of course, the relative importance of other factors need not be the same in both regions. The warmer temperatures in the tropics, for example, suggest that CO_2 fertilization would be more important there (Lloyd and Farquhar1996).

A resolution of the factors responsible for the residual terrestrial flux is of practical concern. If the sink is largely the result of management, it is more acceptable as a C credit under the Kyoto Protocol, especially if it is the result of afforestation or reforestation. On the other hand, if the current sink is largely the result of forest regrowth, the sink is unlikely to persist for more than a few more decades (Hurtt et al. 2002) without additional management practices to sequester C in, for example, degraded lands.

The magnitudes of the C sinks attributable to management, as opposed to environmental effects, could be evaluated in the northern latitudes with a spatial documentation of historical and current changes in land use, including the spatial extent of woody encroachment, and in the tropics with a systematic and spatial determination of rates of deforestation and afforestation, and, to a lesser extent, biomass. As much attention should focus on the fate of downed dead material as on the regrowth of secondary forests. The technical capacity for a systematic monitoring of forest cover in the tropics has existed for 30 years yet still needs to be implemented. The reasons go far beyond C accounting.

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References

Achard, F., H.D. Eva, H.-J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.-P. Malingreau. 2002. Determination of deforestation rates of the world’s humid tropical forests. *Science* **297**, 999-1002.

Asner, G.P., S.A. Archer, R.F. Hughes, J.N. Ansley, and C.A. Wessman. Net changes in regional woody vegetation cover and carbon storage in North Texas rangelands, 1937-1999. *Global Change Biology*. In press.

Asner, G.P., S. Archer, T. Boutton, and H. Johnson. Soil carbon and woody plant proliferation. Submitted to *Nature*.

Aumont, O., J.C. Orr, P. Monfray, W. Ludwig, P. Amiotte-Suchet, and J.-L. Probst. 2001. Riverine-driven interhemispheric transport of carbon. *Global Biogeochemical Cycles* **15**, 393-405.

Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore. 2001. Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science* **294**:1688-1691.

Battle, M., M. Bender, P.P. Tans, J.W.C. White, .J.T. Ellis, T. Conway and R.J. Francey. 2000. Global carbon sinks and their variability, inferred from atmospheric O_2 and $\delta^{13}C$. *Science* **287**, 2467-2470.

Billings, W.D. 1990. *Bromus tectorum*, a biotic cause of ecosystem impoverishment in the Great Basin. *The Earth in Transition. Patterns and Processes of Biotic Impoverishment* (G.M. Woodwell, ed.), pp 301-322. Cambridge University Press, New York.

Bopp, L., C. Le Quéré, M. Heimann, and A. C. Manning. 2002. Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget. *Global Biogeochem. Cycles,* **16**, doi: 10.1029/2001GB001445.

Bousquet, P., P. Peylin, P. Ciais, C. Le Quérè, P. Friedlingstein, and P.P. Tans. 2000. Regional changes in carbon dioxide fluxes of land and oceans since 1980. *Science* **290**, 1342-1346.

Bruno, M., and F. Joos.1997. Terrestrial carbon storage during the past 200 years: A Monte Carlo analysis of CO_2 data from ice core and atmospheric measurements. *Global Biogeochem. Cycles*, **11**, 111-124, 1997.

Caspersen, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcroft, and R.A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. *Science* **290**, 1148-1151.

Chambers, J.Q., N. Higuchi, J.P. Schimel, L.V. Ferreira, and J.M. Melack. 2000. Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia* **122**, 380-388.

Ciais, P., P.P. Tans, J.W.C. White, M. Trolier, R.J. Francey, J.A. Berry, D.R. Randall, P.J. Sellers, J.G. Collatz, and D.S. Schimel. 1995. Partitioning of ocean and land uptake of CO_2 as inferred by $\delta^{13}C$ measurements from the NOAA Climate Monitoring and Diagnostics Laboratory global air sampling network. *Journal of Geophysical Research* **100**, 5051-5070.

Clark, D. 2002. Are tropical forests an important carbon sink? Reanalysis of the long-term plot data. *Ecological Applications* **12**, 3-7.

Conway, T.J., and P.P. Tans. 1999. Development of the CO_2 latitude gradient in recent decades. *Global Biogeochemical Cycles* **13**:821-826.

DeFries, R.S., R.A. Houghton, M.C. Hansen, C.B. Field, D. Skole, J. Townshend. 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. *Proceedings of the National Academy of Sciences* **99**, 14256-14261.

Denning, A.S., I.Y. Fung, and D.A. Randall. 1995. Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota. *Nature* **376**, 240-243.

FAO. 2001. Global forest resources assessment 2000. Main report. FAO Forestry Paper 140, Rome, Italy.

Fearnside, P.M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* **46**, 115-158.

Gaudinski, J.B., S.E. Trumbore, EA. Davidson, and S. Zheng. 2000. Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. *Biogeochemistry* **51**:33-69.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G. H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, and A.Z. Shvidenko. 2002. Forest carbon sinks in the northern hemisphere. *Ecological Applications* **12**, 891-899.

Grace, J., J. Lloyd, J. McIntyre, A.C. Miranda, P. Meir, H.S. Miranda, C. Nobre, J. Moncrieff, J. Massheder, Y. Malhi, I. Wright, and J. Gash. 1995. Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, 1992 to 1993. *Science* **270**, 778-780.

Gruber, N., and C. D. Keeling, An improved estimate of the isotopic air-sea disequilibrium of CO_2: Implications for the oceanic uptake of anthropogenic CO_2. *Geophys. Res. Lett.,* **28**, 555-558, 2001.

Gurney, K.R., R.M. Law, A.S. Denning, P.J. Rayner, D. Baker and coauthors. 2002. Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature* **415**, 626-630.

Heimann, M., and E. Maier-Reimer. 1996. On the relations between the oceanic uptake of CO_2 and its carbon isotopes, *Global Biogeochem. Cycles,* **10***,* 89-110.

Hicke, J.A., R.L. Sherriff, T.T. Veblen, and G.P. Asner. Carbon accumulation in Colorado ponderosa pine stands estimated with dendrochronology. Submitted to *Forest Ecology and Management*.

Houghton, R.A. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus*, in press.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence. 1999. The U.S. carbon budget: contributions from land-use change. *Science* **285**, 574-578.

Houghton, R.A., K.T. Lawrence, J.L. Hackler, and S. Brown. 2001. The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates. *Global Change Biology* **7**, 731-746.

House, J.I., N. Ramankutty, I.C. Prentice, M. Heimann, R.A. Houghton. Reducing uncertainties in the global terrestrial CO_2 sink. *Tellus*, in press.

Joos, F., and M. Bruno. 1998. Long-term variability of the terrestrial and oceanic carbon sinks and the budgets of the carbon isotopes ^{13}C and ^{14}C, *Global Biogeochem. Cycles*, **12**, 277-295.

Joos, F., R. Meyer, M. Bruno, and M. Leuenberger. 1999. The variability in the carbon sinks as reconstructed for the last 1000 years, *Geophys. Res. Lett.,* **26**, 1437-1440.

Joos, F., I.C. Prentice, and J.I. House. 2002. Growth enhancement due to global atmospheric change as predicted by terrestrial ecosystem models: consistent with US forest inventory data. *Global Change Biology* **8**, 299-303.

Keeling, C. D., S. C. Piper, R. B. Bacastrow, M. Wahlen, T. P. Whorf, M. Heimann, and H. A. Meijer. 2001. Exchanges of atmospheric CO_2 and $^{13}CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000: I. Global Aspects. *Scripps Institution of Oceanography Reference Series No. 00-06*, University of California, San Diego, CA, USA.

Keeling, R.F., S.C. Piper, and M. Heimann. 1996. Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentration. *Nature* **381**, 218-221.

Keeling, R.F., and H. Garcia. 2002. The change in oceanic O_2 inventory associated with recent global warming. *Proc. US Natl. Acad. Sci.* **99**:7848-7853.

Keller, M. Asner, G.P., Silva, J.N.M., and M. Palace. (in press) Sustainability of selective logging of upland forests in the Brazilian Amazon: Carbon budgets and remote sensing as tools for evaluation of logging effects. *Working Forests in the Tropics: Conservation Through Sustainable Management?*, D. Zarin, J. Alavalapati, F.E. Putz, M. Schmink (eds.), Columbia University Press, New York.

Keller, M., M. Palace, G.P. Asner, R. Pereira Jr., and J.N.M. Silva. Coarse woody debris in undisturbed and logged forests in the Eastern Brazilian Amazon. Submitted to *Global Change Biology*.

Keller, M., M. Palace, and G. Hurtt. 2002. Biomass estimation in the Tapajos National Forest, Brazil: Examination of sampling and allometric uncertainties. *Forest Ecology and Management* **154**, 371-382.

Kurz, W.A., and M.J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* **9**, 526-547.

Lloyd, J., and G.D. Farquhar. 1996. The CO_2 dependence of photosynthesis, plant growth responses to atmospheric CO_2 concentrations and their interactions with soil nutrient status. I. General principles and forest ecosystems. *Functional Ecology* **10**, 4-32.

Malhi, Y., A.D. Nobre, J. Grace, B. Kruijt, M.G.P. Pereira, A. Culf, and S. Scott. 1998. Carbon dioxide transfer over a central Amazonian rain forest. *Journal of Geophysical Research* **103**, 31593-31612.

Marland, G., T.A. Boden, and R.J. Andres. 2000. Global, regional, and national CO_2 emissions. In: *Trends: A Compendium of Data on Global Change,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN, USA.

Monastersky, R. 1999. The case of the missing carbon dioxide. *Science News* **155**(24), 383.

McGuire, A.D., S. Sitch, J.S. Clein, R. Dargaville, G. Esser, J. Foley, M. Heimann, F. Joos, J. Kaplan, D.W. Kicklighter, R.A. Meier, J.M. Melillo, B. Moore, I.C. Prentice, N. Ramankutty, T.Reichenau, A. Schloss, H. Tian, L.J. Williams, and U. Wittenberg. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land use effects with four process-based ecosystem models. *Global Biogeochemical Cycles* **15**, 183-206.

Miller, S.D., M.L. Goulden, M.C. Menton, H.R. da Rocha, H.C. Freitas, A.M. Figueira, C.A.D. Sousa. Tower-based and biometry-based measurements of tropical forest carbon balance. *Ecological Applications,* in press.

Pacala, S.W., G.C. Hurtt, D. Baker, P. Peylin, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, R.F. Stallard, P. Ciais, P. Moorcroft, J.P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M.E. Harmon, S.-M. Fan, J.L. Sarmiento, C.L.

Goodale, D. Schimel, C.B. Field. 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science* **292**, 2316-2320.

Phillips, O.L., Y. Malhi, N. Higuchi, W.F. Laurance, P.V. Nunez, R.M. Vasquez, S.G. Laurance, S.V. Ferreira, M. Stern, S. Brown, and J. Grace. 1998. Changes in the carbon balance of tropical forests: Evidence from long-term plots. *Science* **282**, 439-442.

Phillips, O.L., Y. Malhi, B. Vinceti, T. Baker, S.L. Lewis, N. Higuchi, W.F. Laurance, P. Núñez Vargas, R. Vásquez Martinez, S. Laurance, L.V. Ferreira, M. Stern, S. Brown, and J. Grace. 2002. Changes in growth of tropical forests: evaluating potential biases. *Ecological Applications* **12**, 576-587.

Plattner, G., F. Joos, and T.F. Stocker. 2002. Revision of the global carbon budget due to changing air-sea oxygen fluxes. *Global Biogeochemical Cycles*, in press.

Prentice I.C., G.D. Farquhar, M.J.R. Fasham, M.L. Goulden, M. Heimann, V.J. Jaramillo, H.S. Kheshgi, C. Le Quéré, R.J. Scholes, D.W.R. Wallace. 2001. The carbon cycle and atmospheric carbon dioxide. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 183-237.

Quay, P. D., B. Tilbrook, and C. S. Won. 1992. Oceanic uptake of fossil fuel CO_2: Carbon-13 evidence. *Science,* **256***,* 74-79.

Rayner, P. J., I. G. Enting, R. J. Francey, and R. Langenfelds. 1999. Reconstructing the recent carbon cycle from atmospheric CO_2, $\delta^{13}C$ and O_2/N_2 observations. *Tellus,* **51B**, 213-232.

Ramankutty, N., and J.A. Foley. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles* **13**, 997-1027.

Rice, A.H., E.H. Pyle, S.R. Saleska, L. Hutyra, P.B. de Camargo, K. Portilho, D.F. Marques, and S.C. Wofsy. Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecological Applications*, in press.

Rundel, P.W., J.R. Ehleringer, and K.A. Nagy. 1989. *Stable Isotopes in Ecological Research*. Springer-Verlag, New York.

Sarmiento, J.L., and E.T. Sundquist. 1992. Revised budget for the oceanic uptake of anthropogenic carbon dioxide. *Nature* ***356***, 589-593.

Schimel, D., J. Melillo, H. Tian, A.D. McGuire, D. Kicklighter, T. Kittel, N. Rosenbloom, S. Running, P. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R.

Neilson, and B. Rizzo. 2000. Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science* **287,** 2004-2006.

Siegenthaler, U. and H. Oeschger, 1987. Biospheric CO2 emsissions during the past 200 years reconstructed by deconvolution of ice core data. *Tellus*, Ser. B, **39**, 140-154.

Spiecker, H., K. Mielikäinen, M. Köhl, and J.P. Skovsgaard (editors). 1996. *Growth Trends in European Forest - Studies from 12 Countries*. Springer-Verlag, Berlin.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. *Science* **247**, 1431-1438.

Tans, P.P., I.Y. Fung, and I.G. Enting. 1995. Storage versus flux budgets: The terrestrial uptake of CO_2 during the 1980s. Pages 351-366 in: G.M. Woodwell and F.T. Mackenzie (editors). *Biotic Feedbacks in the Global Climatic System. Will the Warming Feed the Warming*. Oxford University Press, New York.

Takahashi, T., et al.. 2002. Global sea-air CO_2 flux based on climatological surface ocean $p$$CO_2$, and seasonal biological and temperature effects. *Deep-Sea Res. II,* **49**, 1601-1622.

Townsend, A.R., G.P. Asner, J.W.C. White, and P.P. Tans. 2002. Land use effects on atmospheric ^{13}C imply a sizable terrestrial CO_2 sink in tropical latitudes. *Geophysical Research Letters* **29**, 10.1029/2001GL013454.

Table 1. Global C budgets for the 1980s and 1990s (PgC yr^{-1}). Negative values indicate a withdrawal of CO_2 from the atmosphere.

	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 sink**	-0.4 ± 0.7	-0.7 ± 0.8
Land-use change***	2.0 ± 0.8	2.2 ± 0.8
Residual 'terrestrial' sink	-2.4 ± 1.1	-2.9 ± 1.1

* from Prentice et al. (2001)
** from Plattner et al. (2002)
*** from Houghton (in press)

Table 2. Estimates of the annual terrestrial C sink (PgC yr^{-1}) in the 1990s according to different methods. Negative values indicate a terrestrial sink.

	O_2 and CO_2	Inverse calculations	Forest inventories	Land-use change
Globe	-0.7(±0.8)[1.]	-0.8(±0.8)[2.]	-	2.2(±0.8)[3.]
North	-	-2.1(±0.8)[4.]	-1.4[5.]	0.03(±0.5)[3.]
Tropics	-	1.5(±1.2)[6.]	-0.6[7.]	0.9 to 2.4[8.]

1. Plattner et al. 2002
2. –1.4 from Gurney et al. (2002) reduced by 0.6 to account for river transport (Sarmiento and Sundquist 1992, Tans et al. 1995)
3. Houghton, in press
4. –2.4 from Gurney et al. (2002) increased by 0.3 to account for river transport (Aumont et al. 2001)
5. –0.7 in forests (Goodale et al., 2002) and another equivalent amount assumed for non-forests (see text)
6. 1.2 from Gurney et al. (2002) increased by 0.3 to account for river transport (Aumont et al. 2001)
7. Undisturbed forests: –0.6 from Phillips et al. (1998) (challenged by Clark 2002)
8. 0.9 from DeFries et al., in review
   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 fluxes of C attributed to several mechanisms (average PgC yr^{-1} for the period 1980-1989)

	McGuire et al.*	Houghton
Croplands	0.8**	1.21**
Pastures	NE	0.44
Shifting cultivation	NE	0.24
Logging	NE	0.29
Afforestation	NE	-0.10
Other***	NE	-0.11
CO_2 fertilization	-1.9	NE
Climatic variation	0.4	NE
Total	-0.7	1.97

NE is ‘not estimated’. Negative values indicate a terrestrial sink.

* The estimates from McGuire et al. (2001) are the means of four process-based terrestrial carbon models.

** The simulations in McGuire et al. used net changes in cropland area from Ramankutty and Foley (1999) to calculate flux. The analysis by Houghton included gross rates of clearing and abandonment to calculate the flux attributable to croplands. The clearing of forests for croplands in the tropics exceeds the net increase in cropland area.

*** Fire suppression in the U.S. (-0.150 PgC yr^{-1}) and degradation of forests in China (0.044 PgC yr^{-1})

Table 4. Estimated rates of C accumulation in the U.S. (PgC yr^{-1} in 1990)

	Pacala et al.* (2001) low	Pacala et al.* (2001) 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

NE is ‘not estimated’. Negative values indicate a source of C 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 U.S., they are ignored here.

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

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

**** -0.020 PgC yr^{-1} in forests and -0.026 PgC yr^{-1} in the thickening of western pine woodlands as a result of early fire suppression

Table 5. Estimates of the associated sources (+) and sinks (-) of carbon (PgC 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 of wood	0.190	0.120	0.310
a. Wood 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 U.S. only, and similar values may apply in South America, Australia, and elsewhere.

Table 6. Percentage by which recent estimates of net change in forest area* for the 1990s are lower than reported by the FAO (2001)

	Achard et al. (2002)	DeFries et al. (2002)
Tropical America	18	28
Tropical Asia	20	16
Tropical Africa	42	93
All tropics	23	54

* The net change in forest area is not the rate of deforestation. It is the difference between the rate of deforestation and the rate of afforestation.

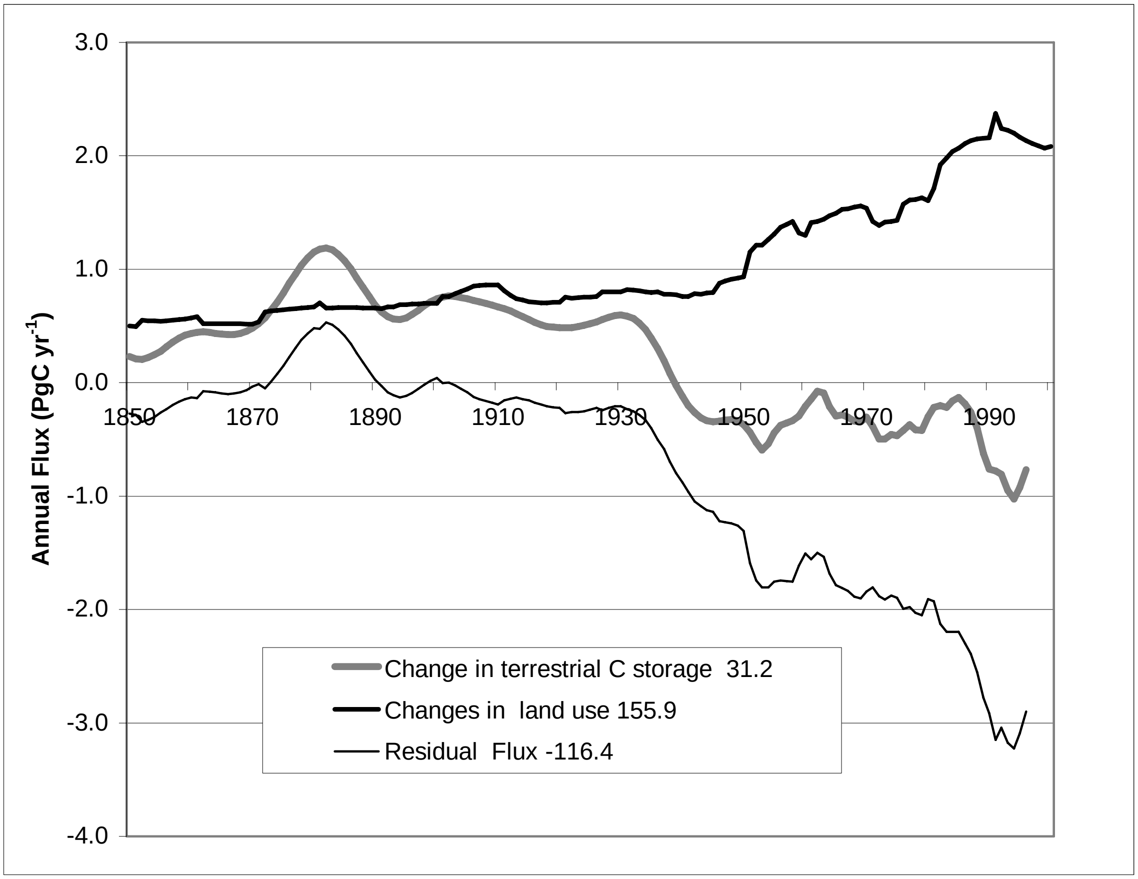

Figure 1. The annual change in global carbon storage in terrestrial ecosystems (Joos et al. (1999, updated), the annual flux from changes in land use (Houghton, in press), and the annual residual terrestrial sink (the difference between the changes in terrestrial storage and the land-use change flux). The values in the legend refer to the total change in C storage or C flux between 1850 and 2000. Negative values indicate a net terrestrial uptake of C. Changes in terrestrial C storage have been estimated by subtracting from fossil emissions the changes in the atmospheric C inventory, deduced from atmospheric and ice core CO_2 data, and in the oceanic C inventory, estimated with an ocean model.