Effects of Land-Use Change on the Carbon Balance of Terrestrial Ecosystems

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Most changes in land use affect the amount of carbon held in vegetation and soil, thereby, either releasing carbon dioxide (a greenhouse gas) to, or removing it from, the atmosphere. The greatest fluxes of carbon result from conversion of forests to open lands (and vice versa). Model-based estimates of the flux of carbon attributable to land-use change are highly variable, however, largely as a result of uncertainties in the areas annually affected by different types of land-use change. Uncertain rates of tropical deforestation, for example, account for more than half of the range in estimates of the global carbon flux. Three other factors account for much of the rest of the uncertainty: (1) the initial stocks of carbon in ecosystems affected by land-use change (i.e., spatial heterogeneity), (2) per hectare changes in carbon stocks in response to different types of land-use change, and (3) legacy effects; that is, the time it takes for carbon stocks to equilibrate following a change in land use. For the tropics, recent satellite-based estimates of deforestation are lower than previous estimates and yield calculated carbon emissions from land-use change that are similar to independently-derived estimates of the total net flux for the region. The similarity suggests that changes in land use account for the net flux of carbon from the tropics. For the northern mid-latitudes, the carbon sink attributed to land-use change is less than the sink obtained by other methods, suggesting either an incomplete accounting of land-use change or the importance of other factors in explaining the current carbon sink in that region.

1. INTRODUCTION

Most changes in land use affect the vegetation and soil of an ecosystem and thus change the amount of carbon held on a hectare of land. The changes may be large, for example, with the conversion of forest to cropland or the reforestation of cleared lands; or they may be negligible, for example, with the replacement of bison by cattle on natural grasslands. Attempts to document the effects of various types of land-use change on carbon stocks have led to numerous calculations from sub-national [*Cohen et al.*, 1996] to national [*Houghton et al.*, 1999; *Hurtt et al.*, 2002; *Houghton and Hackler*, 2003], biome-level [*Achard et al.*, 2002; *DeFries et al.*, 2002], and global scales [*McGuire et al.*, 2001; *Houghton*, 2003]. This review draws heavily on the latest simulation with a book-

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keeping model that estimates the effects of land-use change on global carbon fluxes by using a series of prescribed response curves for different types of ecosystems and land-uses (Figure 1), combined with estimates of the areas of each type of change [*Houghton*, 2003]. The land-use changes included in this analysis are the conversion of natural ecosystems to croplands and pastures, the abandonment of agricultural lands with subsequent recovery of natural vegetation, shifting cultivation, harvest of wood (forestry), plantation establishment, and, in some instances, fire management (exclusion and suppression of fire).

Because of the growing political interest in carbon accounting (the Kyoto Protocol), the definition of land-use change might better be expanded to include all direct human effects on terrestrial carbon storage; that is, various forms of forest and agricultural *management* as well as harvests and land conversion. Such an expanded definition would be consistent with the Marrakech accord under the United Nations Framework Convention on Climate Change, that distinguishes between direct and indirect effects of human activity on carbon stocks. However, subtle management activities, such as forest thinning, low-impact logging, fertilization, selection of species or varieties, and tilling practices, although they affect carbon stocks, have not always been explicitly considered in analyses calculating the sources and sinks of carbon from land-use change. They are not included in the estimates of flux presented here, although their potential effects are discussed below.

The first part of this review focuses on the per hectare changes in vegetation and detrital carbon stocks that result from changes in land use. These changes are considered in order of importance as estimated by current simulations of the net effects of land-use change on global carbon fluxes [*Houghton*, 2003]. We recognize two potential errors in this ranking. First, a small net flux might result from large, uncertain gross fluxes and, thus, not receive appropriate recognition. Second, current estimates of the major land uses contributing to the global carbon flux may be incorrect. We review current estimates of flux to illustrate the range of uncertainty that exists.

In the second part of the paper, we ask whether changes in land use (including management practices, the expanded definition) can explain the net flux of carbon from terrestrial ecosystems. The answer to the question is important for predicting future concentrations of CO_2 in the atmosphere. If the important mechanism for the current terrestrial carbon sink is land-use change (regrowth of forests from abandonment of agriculture, fire supression, logging), the sink is likely to diminish as forests mature. If the important mechanism for the sink is enhanced growth (as, for example, from CO_2 fertilization), it might be expected to continue to grow, at least for some decades (e.g., Prentice et al., 2001). The permanence of the sink affects future concentrations of CO_2 in the atmosphere and, hence, the rate of climatic change.

Determining the relative importance of different factors in explaining the current carbon sink is also important politically because, according to the Marrakech accords, sinks resulting from direct human activity since 1990 may count in offsetting emissions, while sinks resulting from natural processes (for example, disturbance) or indirect human effects (for example, CO_2 fertilization, land-use changes before 1990) will not be credited. Despite its importance, however, attribution is difficult. Furthermore, the direct and indirect human effects do not correspond neatly to convenient categories that might be distinguished, such as regrowth and enhanced growth. While human activity often causes regrowth, natural disturbances (clearly not a direct effect) also lead to regrowth. And,

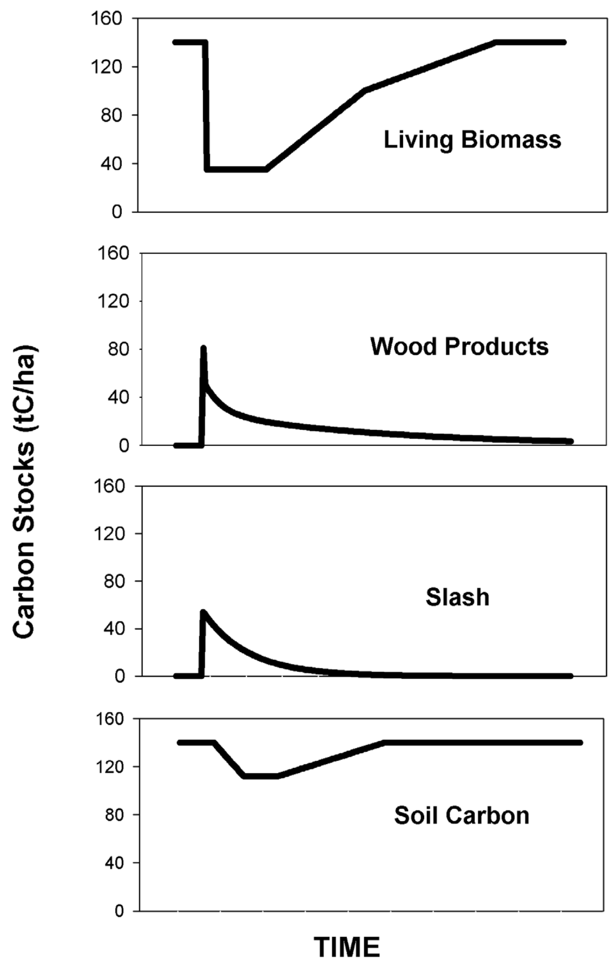

Figure 1. A set of idealized response curves showing the per hectare changes in carbon that follow the clearing of forest for cropland and, subsequently, the recovery of forest on abandoned cropland. Negative slopes indicate a loss of carbon to the atmosphere; positive slopes, the accumulation of carbon on land.

while many indirect effects may enhance growth, so do the direct effects of management.

2. GENERAL UNCERTAINTIES IN CARBON STOCKS THAT APPLY TO ALL TYPES OF LAND-USE CHANGE

Before discussing the specific effects of different types of land-use change on terrestrial carbon stocks, we discuss four issues that pertain to all changes in land use. First, rates of land-use change (for example, hectares of forest converted per year to croplands) and uncertainties in these rates receive little attention in this chapter (see Loveland and DeFries; Verburg et al.; and Klein Goldewijk, this volume). Nevertheless, it is important to recognize that uncertainties associated with rates of land-use change contribute more to uncertainty of carbon fluxes than uncertainties in biophysical variables do. For example, uncertain rates of tropical deforestation account for more than half of the total range of flux estimates for the globe as well as the tropics (see section 4, below).

Second, despite the argument we advance below that per hectare changes in vegetation and soil carbon are reasonably well known for many types of land-use change, the argument assumes a knowledge of initial carbon stocks. For example, the 25–30% loss of organic carbon from the top meter of soil with cultivation is better known than either the initial or ending stocks. Thus the absolute loss of carbon resulting from cultivation is uncertain because of the spatial heterogeneity of initial stocks of soil carbon. The same uncertainty applies to the distribution of biomass. As a result of this inherent property of ecosystems, the initial carbon stocks of lands cleared, harvested, or otherwise modified are not generally documented and are thus poorly known. Spatial scale is important. Carbon stocks may be well known for areas of a hectare or less where measurements exist, but the extrapolation of measured sites to larger areas is largely statistical rather than determined. As a result, despite precise estimates of regional biomass from forest inventories in northern mid-latitude countries, fine-scale spatial variations are less well characterized. In the tropics the scarcity of forest inventories limits understanding of the spatial distribution of forest biomass. A comparison of seven approaches to mapping aboveground biomass in Amazonian forests, for example, showed estimates that varied by more than a factor of two for the total biomass of the region. More importantly, the estimates disagreed as to the distribution of high and low biomass regions [*Houghton et al.*, 2001]. The biomass of forests actually deforested, according to these seven estimates, varied from 25% larger to 32% smaller than the average biomass for the region. Reasons for different estimates of biomass for tropical forests have been discussed by *Brown and Lugo* [1984, 1992], *Fearnside* [1992], and *Fearnside and Laurance* [2003].

Third, the same difficulty (spatial heterogeneity) applies to the amount of carbon disturbed and the resulting or "final" carbon stocks, that is, the equilibrium carbon stocks in a changed ecosystem, either managed or recovered. The magnitude of a carbon sink or source depends on both the initial and final stocks. Finally, the spatial and temporal heterogeneity also contributes uncertainty to rates of decay and regrowth, the processes that determine how long it takes a changed system to equilibrate, to reach a state where the average annual net flux of carbon is approximately zero.

3. EFFECTS OF LAND-USE CHANGE ON CARBON STOCKS

For each of nine types of land-use change below (and Table 1), we briefly review understanding of the effects of that type of land-use change on an ecosystem's vegetation and soil carbon stocks, with consideration of woody debris and wood products pools where appropriate. Land-use change categories are listed in order of their net contribution to the flux of car-

Table 1. Estimates of the annual sources (+) and sinks (-) of carbon during the 1990s (Pg C yr^{-1}) resulting from different types of land-use change and management [from *Houghton*, 2003].

Regions	Tropical	Temperate and boreal zones	Globe
Activities			
Net change in cropland area	1.40	0.043	1.45
Net change in pasture area	0.48	-0.005	0.48
Harvest of wood and regrowth	0.19	0.14	0.34
Shifting cultivation	0.22	0	0.22
Plantations	-0.11	-0.081	-0.19
Fire suppression	0	-0.05	-0.05
Woody encroachment	0	-0.04	-0.04
Other changes in forest area (degradation/restoration)	0	0.001	0.001
Soil management	0	0	0
Total	2.20	0.006	2.21

bon from land-use change during the 1990s, as estimated by a bookkeeping model [*Houghton*, 2003].

The bookkeeping model keeps track of the amount of carbon on each hectare of land affected by land-use change. The amount of carbon in vegetation, slash, wood products, and soil prior to and after a change in land use, as well as the rates of decay and regrowth, are defined in the model by a series of response curves (Figure 1). These response curves vary with the geographic region, the type of ecosystem, and the type of land-use change. The model is driven annually by the number of hectares undergoing a change in land use, that is, by the areas cleared, cultivated, abandoned, harvested, and burned each year. Each change in land use starts a cohort of hectares along one of the response curves. For example, soils may continue to lose carbon for several decades following initial cultivation, and forests may continue to accumulate carbon for centuries after harvest. Thus changes in land use have a legacy that lasts long after the initial change [*Foster et al.*, 2003].

The losses and accumulations of carbon for different ecosystems and different types of land use are summed in the model to calculate the annual net flux of carbon attributable to land-use change. Those lands not known to have been directly affected by human activity are assumed to be in steady state, neither accumulating nor losing carbon. Changes in climate, CO_2, or other environmental variables, and natural disturbances, are ignored, so that the calculated flux is attributable to land-use change alone. As discussed in the second part of this chapter, not all forms of management have been included in the analyses to date. Those types of land use and management that are included are described below.

3.1. Changes in Carbon Stocks as a Result of Net Changes in Cropland Area

The largest estimated net flux of carbon from land-use change is from conversion of natural ecosystems to cropland. Furthermore, the changes in vegetation and soil that result from clearing and cultivation are among the changes in carbon stocks best documented (Table 2). Essentially all of the initial vegetation is replaced by crops, so if the initial vegetation and its biomass are known, it is, in principle, straightforward to calculate the net loss of carbon associated with clearing. Because forests hold so much more carbon per unit area than grasslands, the loss of carbon associated with cropland expansion depends primarily on whether the lands were claimed from forests or open lands. The variation in carbon stocks of different crop types is relatively small as long as tree (permanent) crops are differentiated from herbaceous crops. Some uncertainty results from the lands surrounding and interspersed with croplands; for example, hedgerows, buildings, roads, etc., but these uncertainties are small relative to other factors.

Some uncertainty also results from estimating the time it takes for the release of carbon to occur. How much of the biomass is burned at the time of clearing? What are the rates of decay of stumps and roots? How much woody material is removed from site (wood products) and not decayed immediately?

On average, soil carbon in the upper meter of soil is reduced by 25–30% as a result of cultivation, and this average has been documented in a large number of reviews [*Mann*, 1985, 1986; *Detwiler*, 1986; *Schlesinger*, 1986; *Johnson*, 1992; *Davidson and Ackerman*, 1993; *Post and Kwon*, 2000; *Guo and Gifford*, 2002; *Murty et al.*, 2002] (Table 3). There is some

Table 2. Qualitative estimates of the level of understanding of processes affecting terrestrial carbon stocks.

	Area affected (ha)	Carbon content of			
		Living vegetation	Woody debris	Soil	Wood products
Cultivated land	●	●●	●	●	●
Pasture	●●	●●	●●	●●	●●
Wood harvest	●●	●●	●●	●●	●●
Shifting cultivation	●●●	●●	●●	●●	●●
Plantations	●	●●	●	●●	●
Fire management	●●●	●●	●●	●●	--
Woody encroachment	●●●	●	●	●●●	--
Agricultural management	●	●	--	●	--
Degrade/restore	●●●	●●	●●	●●	●●
Natural disturbance	●●●	●●	●●	●●	--

● Well known.
●● Somewhat known.
●●● Poorly known (individual case studies may be well known, but spatial variation is high or spatial extent is unknown).

Table 3. Soil carbon loss after conversion from native vegetation to cultivated land.

Reference	# Studies	% Soil C lost
Mann 1985	303 sites	-28%
Mann 1986	625 sites	-20%
Johnson 1992	8 papers	-20% (15-25%)
Davidson & Ackerman 1993	18 studies	-30% (20-40%)
Guo & Gifford 2002	37 studies	-42% (34-50%)
Murty et al. 2002	75 studies	-30%
Murty et al. 2002*	33 studies	-22%*
Average		-27%

* studies corrected for bulk density changes.

variation about this average, but the loss is broadly robust across all ecosystems, despite the variety of soil types and cultivation and decomposition processes.

The remaining uncertainty with respect to changes in carbon stocks in response to cultivation concerns the fate of carbon lost from soil. Is all of it, in fact, released to the atmosphere, or is some of it eroded and moved to a different location, perhaps buried in anoxic environments and thereby sequestered? Comparison of erosion rates with the amount of organic carbon in freshwater sediments suggests that much of the carbon lost through erosion may accumulate in riverbeds, lakes, and reservoirs [*Stallard*, 1998; *Smith et al.*, 2001]. To the extent that this is so, the calculated emissions of carbon from croplands are overestimated (Table 1).

When cropland is abandoned, carbon reaccumulates in vegetation as the land reverts to the natural ecosystem. The greater the biomass of the returning ecosystem, the greater the long-term carbon sink associated with recovery. In the short term, however, the magnitude of the annual sink for a particular parcel of land will vary with rate of recovery, which may be affected by the intensity of previous land use or by biophysical factors such as distance from seed source, herbivory, soil fertility, or climatology) [*Uhl et al.*, 1988; *Kozlowski*, 2002]. The rate of recovery of vegetation can also depend on both climate conditions (growing season length) and soil type [*Johnson et al.*, 2000]. Soil carbon may also reaccumulate after abandonment of cultivation, although the rates of carbon accumulation in mineral soil are rather modest [*Post and Kwon*, 2000], especially when compared to the much faster rates of carbon accumulation in vegetation, surface litter, or woody debris [e.g., *Harrison et al.*, 1995; *Huntington*, 1995; *Barford et al.*, 2001; *Hooker and Compton*, 2003]. Globally, carbon accumulation in mineral soils recovering from past tillage is likely to amount to less than 0.1 Pg C yr^{-1} [*Post and Kwon*, 2000].

3.2. Changes in Carbon Stocks as a Result of Net Changes in Pasture and Rangeland Area

The conversion of forest to pastures, largely in Latin America, is the land-use change estimated to be second in importance globally in releasing carbon to the atmosphere (Table 1). Changes in the area of pastures, especially when rangelands are included, are not as well documented as changes in croplands, however. This difference results, in part, from that fact that pastures and rangelands are not easily distinguished from natural grasslands and thus not as well enumerated. Fortunately, the conversion of grasslands to pastures, and vice versa, probably does not involve much of a change in carbon stocks, unless the lands are overgrazed.

The main difference between pastures and croplands is that croplands are cultivated, while pastures are not (if temporary pastures are part of crop rotation, they are considered croplands [*FAO* 2001a]). And if pastures are not cultivated, one might expect little change in soil carbon with the conversion of natural ecosystems to pastures. This is usually the case, although notable changes, both increases and decreases, can occur after conversion [*Post and Kwon*, 2000; *Guo and Gifford*, 2002; *Osher et al.*, 2003; *Parfitt et al.*, 2003]. For example, pasture soils cleared from forests in the Brazilian Amazon have been shown to lose carbon in some cases and gain it in others [*Neill and Davidson*, 2000]. The direction of change may be related to rainfall, site fertility, fertilizer practices, species of grass planted, or other factors that govern the quantity and quality of productivity at a site. In a meta-analysis of 170 studies, *Guo and Gifford* [2002] observed a modest mean increase in soil carbon (about 10%) in upper soil layers (<100 cm) when forests were converted to pastures; however, some sites had large carbon gains and others had large losses.

As with abandoned croplands, abandoned pastures return to the ecosystems they were derived from, accumulating carbon in vegetation and, perhaps, soil over time.

3.3. Changes in Carbon Stocks as a Result of Wood Harvest and Fate of Wood Products

The fluxes of carbon attributed to logging include the losses of carbon from slash (dead material generated as a result of logging) and wood products, as well as the longer term sinks of carbon in trees re-growing after harvest. Because these sources and sinks are to a large extent offsetting, the net flux of carbon attributable to logging is small in comparison to the area annually harvested. Globally, the estimated net effect of these processes is a carbon source, because rates of harvest have been increasing (Table 1). In individual regions, however, the net annual flux may vary (or change sign) as a result of declining harvests or increased efficiency of harvest (a greater fraction of the initial biomass incorporated into long-lasting products).

Estimates of the effects of harvest on vegetation carbon stocks require accurate information on three terms: preharvest biomass, the fraction of this biomass harvested or damaged, and the fraction of the harvested biomass removed from the forest. Wood removed from the forest enters the forest products stream, whereas wood left behind enters the harvest debris or slash pool. Woody debris provides a large source of carbon to the atmosphere as the dead wood decomposes, with rate and duration of this carbon source dependent upon the amount and condition of wood left on-site. The flux of carbon from the dead wood pool is large during the years after harvest, decreases as the slash pool decomposes, and then increases again later in succession as dead wood accumulates [e.g., *Harmon et al.*, 1990; *Idol et al.*, 2001].

Harvesting has little impact on soils relative to most other types of land use. The forest floor often incurs modest losses of carbon for several years after harvest, due largely to several years' worth of reduced carbon inputs and to the mechanical transfer of forest floor material to deeper soil layers [*Currie et al.*, 2002; *Yanai et al.*, 2003]. The degree of mixing is one of several factors that affect the impact of forest harvest on mineral soil carbon stocks. Averaged over a broad range of studies, wood harvest seems to have little mean effect on mineral soil carbon stocks, although this mean reflects the balance of carbon gains observed in some treatments (for example, after sawlog harvests, or under conifers) and notable losses in others (for example, after whole-tree harvests, or under hardwoods) [*Johnson*, 1992; *Johnson and Curtis*, 2001].

The rate of carbon accumulation in vegetation during forest recovery after harvest, as after other disturbances, can vary with climate and soil conditions [*Johnson et al.*, 2000]. Effects of other factors in controlling forest regrowth rate, such as changing atmospheric chemistry (CO_2, biologically available N, discussed in greater detail below) or subtle legacies of different land uses themselves, remain largely undetermined. Because forest harvest usually causes little to no direct loss of soil organic matter, little additional accumulation of soil carbon occurs with forest recovery.

3.4. Changes in Carbon Stocks as a Result of Shifting Cultivation

The estimated flux of carbon from changes in shifting cultivation is highly uncertain in the analysis by *Houghton* [2003], largely because neither the areas in shifting cultivation nor changes in that area are well known. The uncertainty has a potentially large effect on fluxes of carbon because large areas of forest are cleared each year by shifting cultivators, and large areas of land are in fallow (that is, accumulating carbon, at least temporarily). In the cycle of shifting cultivation, forests are cleared (although large trees are often left standing), crops are cultivated for a few years, abandoned, and then cleared and cropped again after a period of fallow. Fallow periods can be long or short, and generally the stocks of carbon in fallow forests recleared for cultivation are less than the stocks in undisturbed forests. Because the cultivation does not involve tillage, the loss of carbon from soil is less than the loss under cultivation of "permanent" croplands. Thus, the per hectare changes in carbon stocks (both biomass and soil) are smaller under shifting cultivation than under permanent cultivation (see section 3.1., above).

In many regions of tropical Asia and Africa, the fallow periods are being reduced as land becomes scarce [*Myers*, 1980; *Uhlig et al.*, 1994]. Often the shortened fallow does not allow the recovery of nutrients necessary for crop production, and this intensification is causing shifting cultivation to become unsustainable (see Lawrence et al., this volume). The net result is an increase in degraded lands that support neither crops nor forests (see section 3.9., below), and a gradual reduction in carbon stocks.

3.5. Changes in Carbon Stocks as a Result of the Establishment of Tree Plantations

The largest increases in plantations were in China and India, although globally the increase in plantations was less than 20% of the area deforested during the 1980s [*FAO*, 1995]. The rate of accumulation of carbon aboveground is well documented for plantations, but the spatial heterogeneity (which types of plantation are planted where?) is not readily available for large regions. For example, plantations may be established for timber, shelter belts, orchards, or fuelwood, and the stocks of carbon in biomass consequently vary. Whether plantations are established on nonforest lands or on recently cleared forests also affects the net changes in biomass and soil carbon that result. Reviewing more than 100 observations, *Guo and Gif-*

ford [2002] found that the establishment of plantations on forest lands or pastures generally decreased soil carbon stocks, while establishment on croplands increased them. In another review *Paul et al.* [2002] found that plantations established on agricultural lands (both croplands and pastures) lost soil carbon during the first 5–10 years but gained it over periods longer than 30 years. The changes in soil carbon were generally small relative to the gains in biomass.

3.6. Changes in Carbon Stocks as a Result of Fire Management

Initially, the prevention and suppression of wildfires increase the stocks of carbon in biomass. After some interval, further accumulation is negligible as a new equilibrium is reached. Conversely, prescribed fires may either maintain or reduce biomass depending on the state of the forests at the initiation of the prescribed burning. The effect of fire on soil carbon is less clear, although fires may consume much of the litter layer. More importantly, fires in forested peatlands may release more carbon from the burning of peat than from the burning of vegetation [*Page et al.*, 2002].

Fire exclusion in the U.S. is estimated to have been responsible for a cumulative net sink of 8–13 Pg C over the period 1850–1990 and 0.05 Pg C/yr during the 1990s (Table 1), offsetting to some extent the cumulative net source of 25 Pg C from other changes in land use [*Houghton et al.*, 2000]. The estimated sink includes only the simulated effects on forests; it does not include the effects of fire exclusion on woody encroachment in non-forest lands (see section 3.7., below). Using a different model, *Hurtt et al.* [2002] estimated a net accumulation of ~0.13 Pg C yr^{-1} in soil and dead wood in western U.S. forests in the 1980s due to fire suppression. The estimated sink for the globe is probably underestimated in Table 1 because the estimate includes only the U.S. However, it is not clear how important fire suppression is for carbon storage in other regions. For example, fire suppression that was initiated hundreds of years ago in parts of Europe may be affecting stocks little at present.

The areas annually burned by fire have been recorded for a century or more in many northern mid-latitude countries, and today satellite data are providing information on burned areas. Large uncertainties, nevertheless, remain in determining exactly what and how much is burned (forests or grasslands? ground vegetation or trees?), how much vegetation is killed and, thus, how much carbon is released (and recovered) in the years following a fire. The importance of fire varies regionally. Large areas of remote boreal forests in Canada and Russia burn; small areas in the highly managed forests of the temperate zone burn. Whether fires are started by human or natural factors (and thus whether they result from management or not) may be difficult to determine.

3.7. Changes in Carbon Stocks as a Result of Woody Encroachment

In many dryland ecosystems, fire suppression, overgrazing, and other management activities have caused woody encroachment, or the expansion of trees and woody shrubs into herbaceous lands. The rate of carbon accumulation due to woody encroachment estimated in Table 1 is for the U.S. alone and likely underestimates the global total [e.g., *Scholes and Archer*, 1997; *Archer et al.*, 2001]. Despite the fact that two estimates of the U.S. carbon sink from woody encroachment are similar [*Houghton et al.*, 1999; *Hurtt et al.*, 2002], the estimate is highly uncertain, largely because the areal extent of woody encroachment is unknown and difficult to measure [e.g., *Asner et al.*, 2003]. Also, in some cases, woody encroachment is accompanied by losses of soil carbon, which partly offset increases in vegetation carbon [*Jackson et al.*, 2002]. In other cases the soils may gain carbon [e.g., *Hibbard et al.*, 2001] or show no discernable change [*Smith and Johnson*, 2003].

3.8. Changes in Carbon Stocks as a Result of Agricultural Management Practices

The changes in soil carbon that result from the conversion of natural ecosystems to croplands and their subsequent cultivation are addressed above (in section 3.1). This section addresses the net flux of carbon resulting from changes in cropland management, including conservation tillage, changes in crop density, changes in crop varieties, fertilization, etc. Many studies have addressed the potential for management to sequester carbon. Fewer studies have tried to estimate past or current carbon sinks. Recent analyses for the U.S. suggest a current sink of 0.015 Pg C yr^{-1} in croplands [*Eve et al.*, 2002], while a recent assessment for Europe suggests a net source of 0.300 Pg C yr^{-1}, perhaps because of reduced application of organic manure to cropland [*Janssens et al.*, 2003]. In Canada the flux of carbon from cropland management is thought to be changing from a net source to a net sink, with a current flux near zero [*Smith et al.*, 2000]. Globally, the current flux is uncertain but probably not far from zero (Table 1).

3.9. Changes in Carbon Stocks as a Result of Other Changes in Forest Area

The estimated flux of carbon from other changes in forest area (land uses not described above) is small, in part because the net flux includes offsetting fluxes (degradation and restoration) and in part because there is little information about areas annually degraded or restored. Examples of degradation as a result of human activity have been inferred from changes in forest area in the tropics [*Houghton*, 1994] and China [*Houghton and Hackler*, 2003]. The increase in "other lands," defined by the *FAO* [2001a] as lands that are not croplands, pastures, or forests and woodlands, suggests that degraded lands are expanding, especially in Africa and Asia, as a result of unsustainable agricultural practices [*Houghton*, 1994]. In China the difference between current forest area and the area believed to have been forested prior to human disturbance is more than twice the area currently in croplands [*Houghton and Hackler*, 2003]. An area greater than the current area of croplands was apparently converted from forests to another land cover. These non-forest lands may have resulted from unsustainable harvests of forests, from deliberate removal of forest cover (for protection from tigers or bandits), and from the deleterious effects of long-term intensive agriculture on soil fertility. Unlike croplands, pastures, and forests, the area in degraded lands is rarely enumerated [*Oldeman*, 1994], yet the losses of carbon may be equivalent to the losses resulting from cultivation. Satellites offer the possibility of improved observations of changes in area (see Loveland and DeFries, this volume).

4. THE IMPORTANCE OF LAND-USE CHANGE IN THE GLOBAL CARBON CYCLE

Globally, we estimate that changes in land use released 156 Pg C to the atmosphere over the period 1850–1990 [*Houghton*, 2003], about half as much as released from combustion of fossil fuels (Figure 2). Soils accounted for about a quarter of the long-term global release, although the fraction was higher in temperate-zone regions and lower in the tropics. During the 1990s the estimated annual flux averaged 2.2 Pg C yr^{-1}, almost entirely from the tropics (Table 1). Outside the tropics, the average flux was a sink of 0.01 Pg C yr^{-1}. Errors for the annual estimates are thought to be approximately $\pm$50% for tropical regions, where annual emissions are substantial. Outside the tropics, percentage errors are inappropriate because the fluxes are near zero. Deforestation dominates the tropical source of carbon. Outside the tropics, the losses of carbon from decay of wood products and slash (from logging) are largely offset by the accumulation of carbon in regrowing forests following harvest.

This estimate of a release of carbon to the atmosphere from changes in land use (a source of 2.2 $\pm$ 0.8 Pg C yr^{-1} in the 1990s) is opposite in sign to the recent estimate obtained from inverse calculations based on atmospheric concentrations of O_2 and CO_2 [*Plattner et al.*, 2002] (Table 4). The difference (2.9 Pg C yr^{-1}) has been referred to as the "missing" carbon sink or the residual terrestrial sink [*Prentice et al.*, 2001]. The explanation for this residual sink is uncertain but was initially attributed to the effects of CO_2 fertilization, N deposition, climatic change, or forest regrowth [*Schimel et al.*, 1996]. Recent analyses, however, have supported the importance of recovery processes (i.e., regrowth) in accounting for the sink in the U.S. [*Houghton et al.*, 1999; *Caspersen et al.*, 2000; *Schimel et al.*, 2000], and it is possible that land-use change

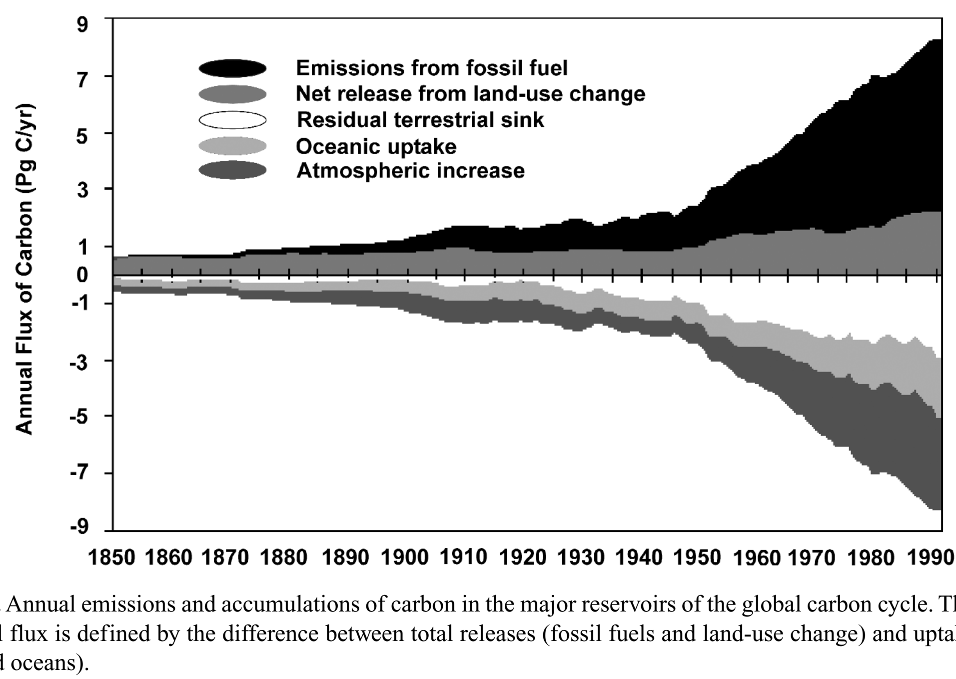

Figure 2. Annual emissions and accumulations of carbon in the major reservoirs of the global carbon cycle. The residual terrestrial flux is defined by the difference between total releases (fossil fuels and land-use change) and uptake (atmosphere and oceans).

Table 4. Global carbon budgets for the 1980s and 1990s (Pg C 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 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

* from *Prentice et al.* [2001].
** from *Plattner et al.* [2002].
*** from *Houghton* [2003].

(including management), together with recovery from past natural disturbances, accounts for the entire terrestrial net flux. Reconciling the disparate global estimates requires consideration of the different processes occurring in the tropics and temperate zones.

4.1. The Tropics

In the tropics, the net flux inferred from inverse analyses with atmospheric data [*Gurney et al.*, 2002], corrected for river transport of carbon [*Aumont et al.*, 2001], overlaps the estimate from land-use change [*Houghton*, 2003] (sources of 1.5 ± 1.2 and 2.2 ± 0.8 Pg C yr^{-1}, respectively) (Table 5). The estimates may be said to agree, although the errors are too large to rule out the possibility that processes other than land-use change are important.

The two estimates become even more similar if the tropical source of carbon from land-use change is calculated from recent, satellite-based estimates of the area of tropical deforestation rather than from the FAO deforestation area statistics [*FAO*, 2001b] that *Houghton* [2003] used. By using intensive satellite data to monitor deforestation "hotspots," *Achard et al.* [2002] found deforestation rates of wet tropical forests to be 23% lower than reported by the *FAO* [2001b]. Based on the lower rates of deforestation and including changes in the area of dry forests as well as humid ones, *Achard et al.* [2002] estimated the tropical source to be 0.96 Pg C yr^{-1}. The estimate may be low, however, because it does not include the losses of carbon from soil 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* [2003] estimated flux of carbon for tropical Asia and America and, if applied to the estimate by *Archard et al.*, would yield a total flux of 1.3 Pg C yr^{-1}. The value is very close to the source of 1.5 Pg C yr^{-1} obtained from the inverse analyses (Table 5). *DeFries et al.* [2002] used an independent, coarse-resolution but comprehensive, satellite-based approach to estimate tropical deforestation for both the wet and dry tropics. This approach also yielded an estimate of deforestation that was lower than reported by the FAO (Figure 3). Using the lower rate gave an estimated net flux of carbon for the 1990s of 0.9 (range 0.5–1.4) Pg C yr^{-1}, lower than but overlapping with the atmospheric-based estimate.

Except for dry tropical Africa, both satellite-based approaches suggest that *FAO* [2001b] overestimates the area of tropical deforestation by about 25%. The percent tree cover mapped by *DeFries et al.* [2002] is least reliable in dry tropical Africa because of the large areas of savanna; yet this uncertainty should influence estimates of net carbon flux little, as the initial carbon stocks of dry savannas are much lower than for wet tropical forests. The tropical emissions of

Table 5. Estimates of the annual terrestrial flux of carbon (Pg C yr^{-1}) in the 1990s according to different methods. Negative values indicate a terrestrial sink.

	O_2 and CO_2	Inverse calculations CO_2, $^{13}CO_2$, O_2	Forest inventories	Land-use change
Globe	-0.7 (±0.8)[1.]	-0.8 (±0.8)[2.]	-	2.2 (±0.6)[3.]
Northern mid-latitudes	-	-2.1 (±0.8)[4.]	-0.6 to -1.3[5.]	-0.03 (±0.5)[3.]
Tropics	-	1.5 (±1.2)[6.]	-0.6 (±0.3)[7.]	0.5 to 3.0[8.]

1. *Plattner et al.* [2002].
2. –1.4 (±0.8) from *Gurney et al.* [2002] reduced by 0.6 to account for river transport [*Aumont et al.*, 2001].
3. *Houghton* [2003].
4. –2.4 from *Gurney et al.* [2002] reduced by 0.3 to account for river transport [*Aumont et al.*, 2001].
5. –0.65 in forests [*Goodale et al.*, 2002] and another 0.0 to 0.65 assumed for non-forests.
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 (range 0.5 to 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* [2003]; 2.4 from *Fearnside* [2000].

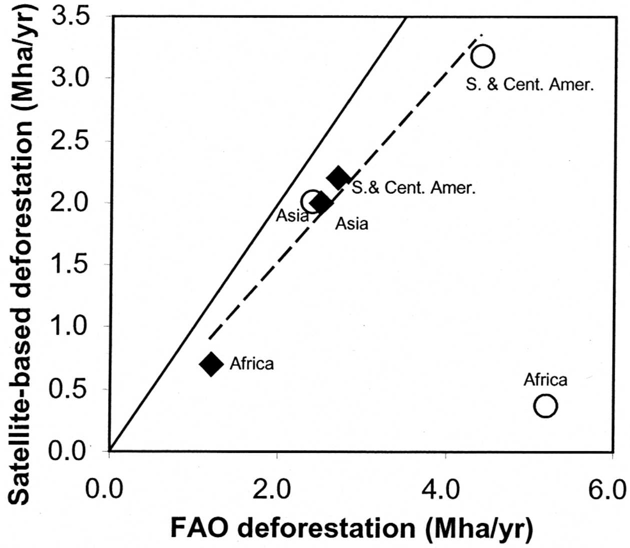

Figure 3. Comparison between satellite-based and FAO-based [*FAO*, 2001b] estimates of annual deforestation rates. Open circles indicate estimates for combined wet and dry tropical forests [*DeFries et al.*, 2002]; closed diamonds indicate estimates for wet tropical forest only [*Achard et al.*, 2002]. The solid line indicates the 1:1 line; the dashed line, the regression line (excluding the *DeFries et al.* [2002] estimate for Africa, $y = 0.76x$, $r^2 = 0.96$).

carbon estimated by the two studies (after adjustments for degradation and soils; 1.3 and 0.9 Pg C yr^{-1}) are about half of *Houghton's* estimate (2.2 Pg C yr^{-1}). The fact that deforestation differences of ~25% yielded flux differences of ~50% is puzzling, but probably explained by the losses of carbon from logging, shifting cultivation, and other activities (included in Houghton's analysis) that reduce the carbon stocks of forests without changing forest area (deforestation). Further differences may result from the estimates of biomass used for the forests actually deforested [*Eva et al.*, 2003; *Fearnside and Laurance*, 2003].

For the tropics, available evidence suggests two possible explanations for the net flux of carbon obtained from atmospheric data (Table 5). Either large emissions of carbon from land-use change [*Fearnside*, 2000; *Houghton*, 2003] are somewhat offset by large carbon sinks in undisturbed forests [*Phillips et al.*, 1998, 2002], or lower releases of carbon from land-use change [*Archard et al.*, 2002; *DeFries et al.*, 2002] explain the entire net terrestrial flux, with essentially no requirement for an additional sink. The second alternative suggests that land-use change dominates the net flux of carbon from the tropics. Nevertheless, rates of deforestation and land degradation remain uncertain (see Loveland and DeFries, this volume) and continue to overwhelm the uncertainty surrounding estimates of the global terrestrial flux of carbon.

4.2. Northern Temperate and Boreal Zones

Attributing the large net sink in northern mid-latitudes found from atmospheric analyses [*Gurney et al.*, 2002] (2.1 $\pm$ 0.8 Pg C yr^{-1} when adjusted for the flux of carbon in rivers [*Aumont et al.*, 2001]) to land-use change is more difficult because the sink attributed to land-use change is very small [*Houghton*, 2003] (Table 5). Three possibilities exist. First, there may be errors in the analyses; second, there may be omissions from the analysis of land-use change; and third, something other than land-use change may be responsible for the difference.

4.2.1. Errors. The first part of this paper deals with the uncertainties in estimating changes in carbon stocks per hectare. If, for example, old-aged forests accumulate carbon more rapidly than assumed, or if spatial differences in climate, soils, and vegetation yield higher growth rates in recovering forests than those used in *Houghton's* [2003] analysis, the analyses will have underestimated the current sink. Uncertainty in the rates of growth and decay are of little importance over large temporal (multiple decades to centuries) and spatial scales because high rates of regrowth diminish the time to recovery, and fewer forests will be regrowing (more will have recovered). Thus, high rates for a smaller regrowing area give a flux nearly equivalent to low rates over a large regrowing area. The interaction between rate of growth and area regrowing tends to minimize the sensitivity of net flux to growth rates. A similar interaction occurs between decay rates and size of pool remaining to decay. However, these offsetting interactions may not apply in the short term (years to decades) or in regions where rates of land-use change are highly variable in time. This potential bias may be particularly important in the northern temperate zone, where rates of land-use change and areas of regrowing forests have varied markedly over the last century. In this region, different assumptions about rates of regrowth can yield quite different estimates of net carbon balance for any particular decade. A comparison of analyses by *Houghton et al.* [1999] and *Hurtt et al.* [2002] illustrates the difference. Both analyses used similar land-use reconstructions but different rates of forest growth. *Houghton et al.* [1999] assumed that regrowth was most rapid early in a forest's recovery; *Hurtt et al.* [2002] assumed it was most rapid later. As a consequence, *Hurtt et al.* [2002] calculated a larger net carbon sink in regrowing vegetation during the 1990s (0.10 Pg C y^{-1}) than did *Houghton et al.* [1999] (0.02 Pg C y^{-1}).

4.2.2. Omissions from the analysis. Not all types of land-use change (broadly defined) were included in the analysis by *Houghton* [2003]. Three omissions believed to be important are described below. First, slash generated as a result of land-use change was included in the analysis, but the stocks, decay, and recovery of *natural* coarse woody debris were not. Thus, the current accumulation of coarse woody debris in regrowing forests was not included in the model, and the calculated sink may, thereby, be underestimated. Second, rates of agricultural clearing and abandonment were underestimated because they were based on net changes in agricultural area when, in fact, simultaneous clearing and abandonment generates a greater area of regrowing forests (and greater carbon sink) than determined in the analysis. Third, forest and agricultural management practices (other than harvest and regrowth and clearing and abandonment, respectively) were not included in the analysis and may be contributing to the current carbon sink [*Spiecker et al.*, 1996].

4.2.3. Something other than land-use change is contributing to the current sink. Two factors other than land-use change and management may contribute to the current northern mid-latitude carbon sink. One factor is natural disturbance. Recovery from past natural disturbances (not included in analyses of land-use change) are responsible for an unknown amount of carbon uptake. Second, environmentally enhanced rates of growth may also contribute. Regrowth (following logging, agricultural abandonment, and fire management) was included in the analyses, but not enhanced growth, as might result from CO_2 fertilization, N deposition, or changes in temperature and moisture. Furthermore, as discussed in the first part of section 3, lands not known to have been affected by land-use change were assumed in the analyses to be unchanged in carbon stocks. In regions such as Canada and Russia, the area of land not directly managed, yet perhaps experiencing either recovery from past disturbance or enhanced growth, is significant.

A comparison of the estimated flux of carbon from land-use change with the estimate determined from data from forest inventories suggests the types of errors and omissions that may be important. The total forest sink in northern mid-latitudes obtained from inventory data (0.6–0.7 Pg C yr^{-1}) [*Goodale et al.*, 2002] includes sources and sinks of carbon in living vegetation, slash and dead wood, wood products, and soils. A region-by-region comparison of the living vegetation, alone, suggests that the recovery of forests from land-use change may either over- or underestimate the sinks obtained from forest inventories (Table 6). In the boreal forests of Canada and Russia, the carbon sink attributed to forests recovering from harvests (land-use change) is greater than the sink estimated from forest inventory data. The difference could be error, but it is consistent with the fact that increased fires and insect damage during the 1980s led to a net loss of living biomass (a net source) [*Kurz and Apps*, 1999]. Such disturbances are recorded in the inventory data but do not appear in the analysis of land-use change because natural disturbances were ignored. In time, the recovery of these disturbed forests will likely increase the sink in vegetation above that calculated on the basis of harvests alone, but at present the losses of carbon from disturbance are greater than the uptake attributable to harvests.

In the three other regions (Table 6), changes in land use show a smaller sink than calculated from forest inventory data. If the results are not simply a reflection of error, the failure of past changes in land use to explain the measured sink suggests that other factors have enhanced the storage of carbon in forests. As mentioned above, the factors include a reduction in past natural disturbances, more subtle forms of management than recovery from harvest and agricultural abandonment, and environmental changes that may have enhanced forest growth. Analysis of forest inventory data from five states in the U.S. led *Caspersen et al.* [2000] to conclude that very little of the observed accumulation of carbon in trees could be attributed to enhanced growth. Instead, it was largely explained by recovery from earlier disturbance. Those results suggest that management and past disturbances are the factors explaining the difference between land-use and inventory estimates of forest growth.

The differences in forest growth between the two approaches are small, generally less than 0.1 Pg C yr^{-1} in any region and only 0.1 Pg C yr^{-1} for the northern mid-latitude forests combined (Table 6). Because the difference between them is greater

Table 6. Annual net change in the living vegetation of forests (Pg C yr^{-1}) in northern mid-latitude regions around the year 1990 according to two analyses. Negative values indicate an increase in carbon stocks (that is, a terrestrial sink).

Region	Land-use change [*Houghton*, 2003]	Forest inventory [*Goodale et al.*, 2002]	Sink from land-use change relative to inventoried sink
Canada	-0.025	0.040	0.065 larger
Russia	-0.055	0.040	0.095 larger
U.S.A.	-0.035	-0.110	0.075 smaller
China	0.075	-0.040	0.115 smaller
Europe	-0.020	-0.090	0.070 smaller
Total	-0.060	-0.160	0.100 smaller

when all components are considered (slash, wood products, and soils in addition to living biomass) (Table 5), the major differences between approaches appears to be associated with errors in accounting for these other pools. Future research should focus on the data and assumptions used to account these other pools.

5. CONCLUSIONS

Despite uncertainties in carbon stocks and rates of growth and decay, the largest fluxes of carbon result from the clearing of forests for croplands, in part because a hectare of trees holds so much more carbon than a hectare of crops, and in part because 25–30% of the carbon in the top meter of soil in a natural ecosystem is lost with cultivation. Carbon fluxes from biogeochemical processes of decay and regrowth are relatively well quantified compared with knowledge of areas undergoing land-use change and other types of disturbance. In particular, uncertainties in the current rate of tropical deforestation and in the dynamics of lands not normally censused (that is, lands that are neither croplands, pastures, nor forests) limit the accuracy of the estimated terrestrial carbon balance.

While we cannot say with confidence that changes in land use, including management, explain both the net tropical source of carbon and the net temperate-zone sink, it appears that land-use change is a dominant factor in accounting for current and past terrestrial sources and sinks of atmospheric carbon dioxide. New estimates of tropical deforestation yield an estimated tropical source of carbon that is similar to the source inferred from atmospheric data and analyses. In the northern mid-latitudes, the sink calculated from changes in land use is smaller than the sink determined from either forest inventories or atmospheric analyses. The difference may be the result of inaccurate or incomplete accounting for management in analyses of land-use change or from the effects of a changing environment on rates of forest growth and carbon accumulation. Distinguishing between these two explanations (regrowth versus enhanced growth) is necessary both for crediting carbon sinks under the United Nations Framework Convention on Climate Change and for predicting whether the current terrestrial carbon sink can be expected to continue in the future.

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