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Terrestrial sources and sinks of carbon inferred from terrestrial data

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ABSTRACT

Two approaches have been used to calculate changes in terrestrial carbon storage with data obtained from terrestrial ecosystems, rather than with atmospheric or oceanographic data. One approach is based on the changes in carbon that result from changes in land use (conversion of forest to agricultural land, abandonment of agricultural land, harvest and regrowth). The other approach uses measurements of forest biomass obtained through forests inventories to determine change directly. These latter studies may also calculate changes in the amount of carbon stored in wood products and soil, but in this respect the two approaches are similar. If a significant fraction of the missing carbon sink is to be found in mid-latitude forests, one would expect direct measurement of biomass to show greater accumulations of carbon than analyses in which calculated accumulations result only from regrowth following previous harvests or abandonment of agricultural land. Data from Canada, the conterminous US, Europe, and the former USSR show this circumstance to be correct. Accumulations of carbon in biomass and soil are 0.8 PgC yr^{-1} greater than expected from past management practices (land-use change). In the tropics (where forest inventories are rare), the total net flux of carbon from changes in land use (1.6 PgC yr^{-1}) is consistent with recent estimates of flux based on atmospheric data, but the geographic distribution of the flux is not the same. Globally, terrestrial ecosystems are calculated to have been a net source of 0.8 ± 0.6 PgC yr^{-1} during the 1980s.

1. Introduction

For about 25 years, scientists have been uncertain as to how the global carbon cycle is balanced. Analyses based on models of oceanic uptake have consistently required a terrestrial sink for carbon (Bacastow and Keeling, 1973; Broecker et al., 1979; Keeling et al., 1989, Sarmiento et al., 1992), and more recently models of atmospheric transport using atmospheric CO_2 data suggest large terrestrial sinks in middle latitudes of the northern hemisphere (Tans et al., 1990, Ciais et al., 1995). In contrast to these geochemical analyses based on atmospheric and oceanic data, analyses based on changes in land use have consistently found global terrestrial ecosystems to be a source of carbon, although large regions may be net sinks (Woodwell et al., 1978, 1983; Houghton et al., 1983, 1985, 1987; Detwiler and Hall, 1988; Hall and Uhlig, 1991; Dixon et al., 1994; Houghton and Hackler, 1995). For the 1980s, the global budget shows the imbalance to be approximately 1.4 ($\pm$1.5) PgC (Schimel et al., 1995) (units are PgC yr^{-1}):

$$\begin{array}{ccc} \text{atmospheric increase} = & \text{fossil fuel} & + \text{ land-use change} \\ 3.2(\pm 0.2) & = 5.5(\pm 0.5) & + 1.6(\pm 1.0) \end{array}$$

$$\begin{array}{ccc} -\text{ocean} & - \text{ uptake by northern forests} & - \text{ residual sink} \\ -2.0(\pm 0.8) & - \; 0.5(\pm 0.5) & -1.4(\pm 1.5) \end{array} \quad (1)$$

Estimates of the net flux of carbon between the atmosphere and terrestrial ecosystems vary most for northern temperate zone and boreal forests

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(the mid-latitudes) (Table 1), and the different estimates are related to the methods used in analysis. The first part of this paper explores the reasons for different estimates of flux in the northern temperate zone and considers some of the implications. The second part of the paper addresses the flux of carbon from tropical deforestation and determines its distribution between northern and southern hemispheres.

2. Temperate zone forests

2.1. Two types of analyses

Those studies that have found the northern temperate zone and boreal lands to be approximately balanced with respect to carbon are based on changes in land use (Melillo et al., 1988; Houghton, 1993; Houghton and Hackler, 1995) (Table 1). Those estimates finding a carbon sink in northern regions are based on data from forest inventories (Dixon et al., 1994; Schimel et al., 1995). The important difference between the two approaches is that analyses based on land-use change compute accumulations of carbon only as they result from deliberate human activity; that is, from forest regrowth following logging, reforestation, or abandonment of agriculture. In contrast, forest inventories measure biomass directly, and accumulations between inventories may result not only from regrowth following land management but from regrowth following previous natural disturbances or from enhanced growth due to changing environmental conditions, such as climate, nitrogen availability, and CO_2 fertilization. Data from forest inventories represent actual accumulations from all causes; calculations based on land-use change consider only the affect of previous human activity on current accumulations.

If the two approaches give similar estimates of flux, then land-use change can be assumed to account for that net flux, and other processes that affect carbon storage can be assumed to be small or compensating each other. If, as seems to be the case, data from forest inventories show greater accumulations of carbon than analyses based on land-use change, explanation and quantification of the difference may help identify the factors responsible. For example, are the differences related to geographical region? Are they related to different rates of growth, different accounting procedures for harvested products, or different rates of carbon accumulation in soils?

2.2. Analyses based on land-use change

A more nearly complete description of the data, assumptions, and methods used in analyses of land-use change is given in Houghton and Hackler (1995). In this approach, the accumulation of carbon was based on (1) the areas of regrowing forests and (2) ecosystem-specific rates of growth in these areas. The areas of regrowing forests, in turn, were determined by the areas annually harvested since about 1700 (Houghton et al., 1983; Melillo et al., 1988; Houghton and Hackler, 1995). The area harvested was determined from the total amount of wood harvested (m^3) (FAO 1992 and other sources before 1950) and average removal rates (m^3 ha^{-1}). Ecosystem-specific rates of growth in forests recovering from logging (and abandonment of agricultural land) were obtained from the ecological and forestry literature. These rates of growth were assumed not to have changed over the last 300 years.

The results for northern temperate and boreal zones (Canada, the US, Europe, and the former Soviet Union) are shown in Fig. 1. The mean flux of carbon between 1975 and 1980 was a small net release to the atmosphere, not different from zero. Carbon was lost from living biomass and soils; carbon accumulated in wood products and slash

Table 1. *Recent estimates of the net flux of carbon to the atmosphere from terrestrial ecosystems*

	Dixon et al. (1994)	Schimel et al. (1995)	Houghton and Hackler (1995)	This study
temperate & boreal	-0.74 ± 0.1	-0.5 ± 0.5	0.0 ± 0.5	-0.8 ± 0.4
tropical	1.65 ± 0.4	1.6 ± 1.0	1.6 ± 0.5	1.6 ± 0.5
global	0.9 ± 0.4	1.1 ± 1.1	1.6 ± 0.7	0.8 ± 0.6

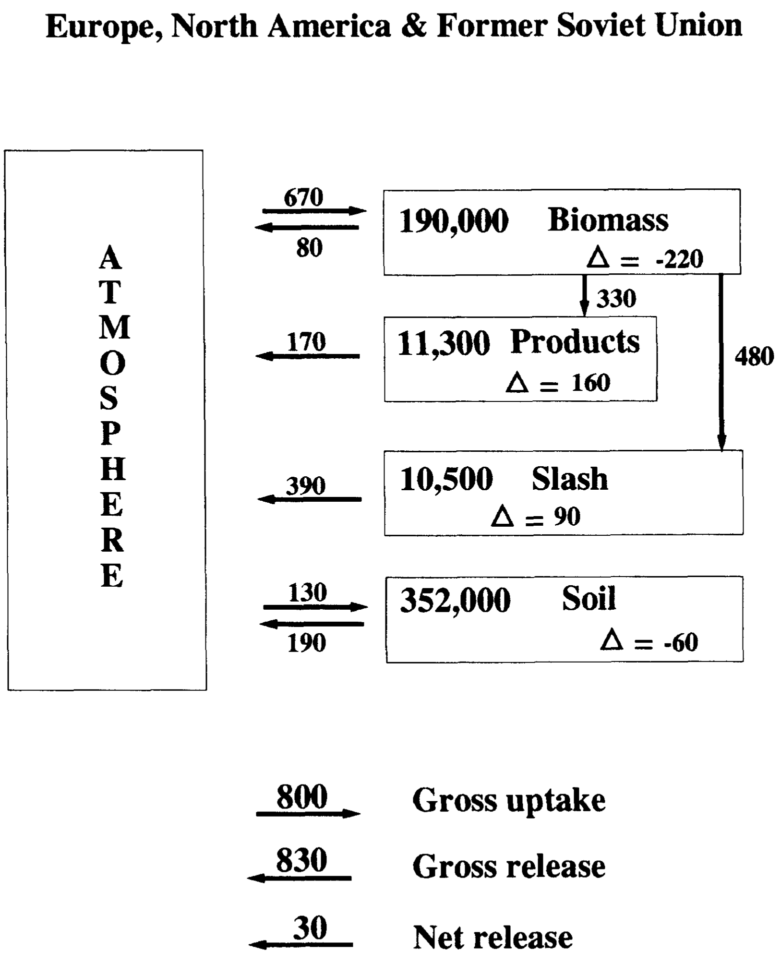

Fig. 1. Changes in the major pools of carbon in temperate and boreal ecosystems, and average annual exchanges of carbon between these pools and the atmosphere between 1975 and 1980 (based on analyses by Houghton and Hackler, 1995).

(woody debris generated as a result of logging). The uptake of carbon associated with regrowth (800 Tg) (670 Tg in biomass; 130 Tg in soils) was approximately balanced by the releases of carbon from burning (80 Tg) and from decay of slash (390 Tg), products (170 Tg), and soil organic matter (190 Tg). A small portion of the flux (20 Tg) came from outside the forest; that is, from oxidation of grassland soils brought under cultivation within the last 50 years and still losing carbon.

2.3. *Analyses based on data from forest inventories*

The data of forest inventories are largely independent of the data used in analyses based on changes in land use. Inventories measure volumes of wood (or stock), annual increments (growth), and removals (amount of wood harvested). The accumulation or loss of carbon can be determined either by the change in stocks (between two inventories) or by the difference between increments and removals of wood volumes, once wood volumes are converted to carbon. The annual removals of wood, as obtained by forest inventories, should be identical to the values used in analyses of land-use change to calculate the areas harvested (and regrowing). In this respect the two approaches are not independent; but the areas of regrowing forests and the rates of carbon accumulation in forests are determined independently. In analyses of land-use change, regrowing areas are a function of previous logging rates. In forest inventories, the areas in different age classes are measured directly. Because of natural disturbances (fire, insects, disease), the total area of regrowing forests may be larger than the area regrowing as a result of harvest or agricultural abandonment alone (Kurz et al., 1995).

The other major difference between the two approaches is that ecosystems not affected by direct human activity are ignored in analyses based on land-use change. Forest inventories cover a much larger area of forests, including both managed and unmanaged forests, but not necessarily all forests. In Canada and Russia, for example, the inventories reported by the ECE/FAO (1992) included only exploitable forests, 45% and 55% of the total area of forests in these countries.

The following discussion summarizes recent estimates of carbon balance for the forests of Canada, the US, Europe, and the former USSR. For each country or region the results are presented in a diagram (Fig. 1) similar to that used by Apps and Kurz (1994). The advantage of displaying the results with this diagram is that estimates of exchange with the atmosphere and estimates of change in terrestrial pools of carbon are both shown. Thus results presented in different ways can be compared. Furthermore, the diagram is less ambiguous than verbal descriptions because terms such as growth and storage, for example, may refer to either amounts or rates, and to either gross or net changes. Adherence to the diagram also helps identify possible errors or omissions in the budgets that have been constructed.

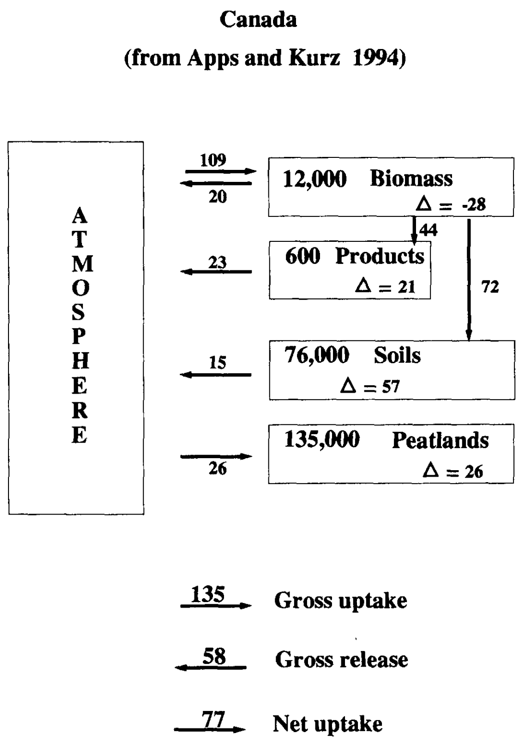

Fig. 2. Changes in the major pools of carbon in Canadian forests, and annual exchanges of carbon between these pools and the atmosphere in 1986 (based on analyses by Apps and Kurz, 1994).

2.3.1. Canada. The carbon balance for Canadian forests is shown in Fig. 2 from Apps and Kurz (1994). For the year 1986, the net flux was an accumulation of 77 TgC on land. Living biomass decreased, while the other three pools increased in carbon content. Some of the exchanges resulted from human disturbances (for example, harvest), some resulted from natural processes, and most were a combination of both. The uptake of 109 TgC by living biomass includes both; that is, growth as a result of aging and natural disturbances and growth following harvest. The release of 20 TgC from living biomass represents a loss to the atmosphere as a result of disturbance, in this case fire. The transfer of 72 TgC from living biomass to soils was in part from natural litterfall (17 Tg) and in part from woody debris generated during disturbances (55 Tg), only a portion of which resulted from logging or other land-use effects. All of the accumulation of carbon in peatlands was independent of land-use change.

2.3.2. Conterminous US. The carbon budget for the forests of the conterminous US (from Turner et al., 1995) is shown in Fig. 3. Their separate accounting for trees and understory vegetation was combined here. The net flux was an accumulation of 79 TgC. The analysis differs from that by Apps and Kurz (1994) in several respects. For example, Turner et al. (1995) included a pool of woody debris, which was contained in the soil pool of Apps and Kurz. Also, the uptake and loss

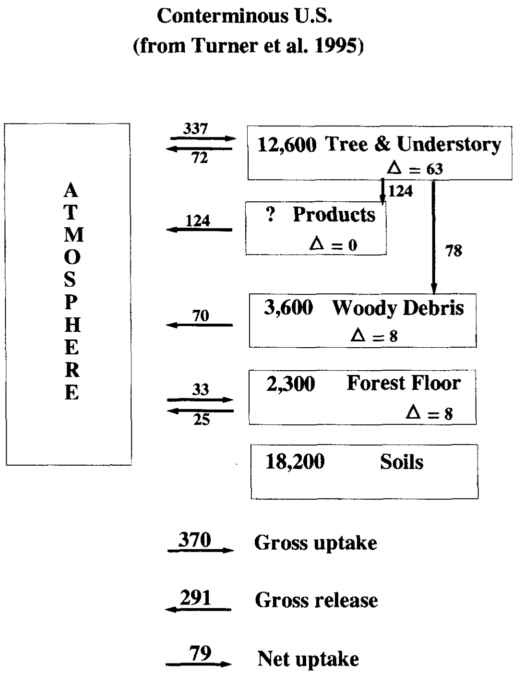

Fig. 3. Changes in the major pools of carbon in forests of the conterminous United States, and average annual exchanges of carbon between these pools and the atmosphere (based on analyses by Turner et al., 1995).

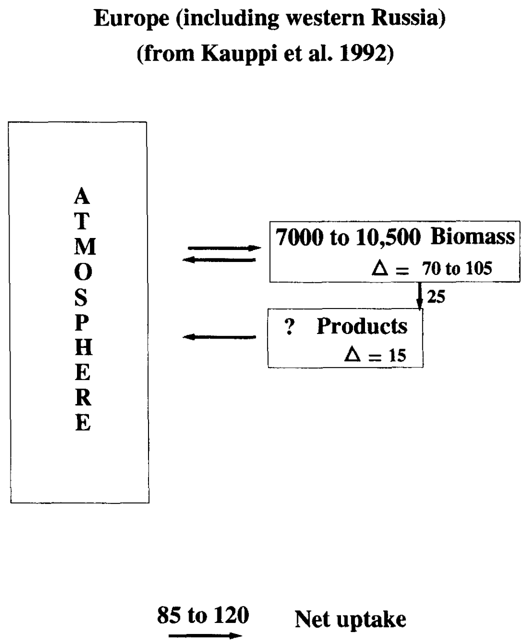

Fig. 4. Changes in the major pools of carbon in European forests, and annual exchanges of carbon between these pools and the atmosphere in 1990 (based on analyses by Kauppi et al., 1992).

of carbon by soils (forest floor) was modeled independently of litter production, so changes in soil carbon resulted from exchanges with the atmosphere only. Turner et al. (1995) did not consider the fate of wood products; their budget was for the forests alone. Presumably the annual accumulation of wood products would retain some of the 124 TgC of wood harvested, and the amount released to the atmosphere would be less than 124 Tg. Thus the net accumulation of carbon in the forests and products of the conterminous US might be somewhat more than 79 TgC annually.

2.3.3. Europe. The results for Europe are based on the analysis by Kauppi et al. (1992) who considered only living biomass and wood products (Fig. 4). In fact, wood products included only saw wood and wood panels; paper products were assumed not to contribute significantly to the accumulation of carbon on land. Ignoring changes in slash and soils, the net accumulation of carbon in European forests, including some of western Russia, was 85 to 120 TgC.

2.3.4. Former USSR. A summary of the results from Kolchugina and Vinson (1993) for the former Soviet Union are shown in Fig. 5. They estimated a net accumulation of 485 TgC for the years around 1980 without considering accumulations of either woody debris or products. The individual fluxes shown in Fig. 5 are different from the summary diagram of Kolchugina and Vinson (1993) (their Fig. 7) because their emissions from wood harvest were disaggregated here into fuelwood (24 Tg of the 223 Tg released from biomass), decay of products (46 Tg), and decay of slash (82 Tg).

2.3.5. Summary budget for all four regions. A comparison of the results of analyses based on data from forest inventories with those based on land-use change is presented below. In the interest of economy, the results are not presented region by region but for the combined temperate zone and boreal forests of Canada, conterminous US, Europe, and the former USSR. Before summing the individual fluxes in Figs. 2–5, however, some of the budgets were modified from those originally published.

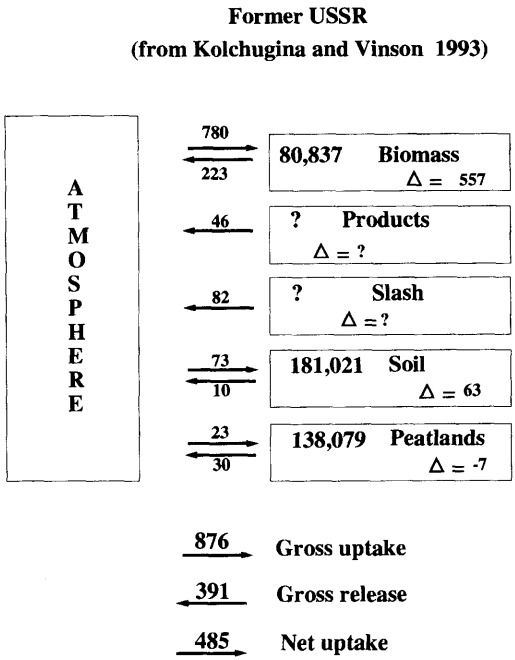

Fig. 5. Changes in the major pools of carbon in forests of the former USSR, and average annual exchanges of carbon between these pools and the atmosphere (based on analyses by Kolchugina and Vinson, 1993).

First, because most analyses did not consider the transfer of carbon from living biomass to soils, the results of Apps and Kurz (1994) were modified to exclude this transfer. The transfer is closer to reality than an uptake of carbon by soil directly from the atmosphere, but adjusting the other analyses was impossible from the data provided. The 72 TgC transfer was eliminated from Fig. 2. The modification required a reduction of the same magnitude in the uptake of carbon by living biomass and a direct transfer of the same magnitude from the atmosphere to soils. The net changes in pools remained unaffected.

For the conterminous US, carbon was assumed to accumulate in wood products. The amount accumulating (59 Tg) and the amount released to the atmosphere (65 Tg) were calculated assuming that the ratios reported for Canada (Apps and Kurz, 1994) (Fig. 2) applied to the US. The modification had the effect of increasing the net accumulation by 59 TgC.

No changes were made to the analysis for Europe to account for the accumulation of carbon in slash or soils, or for exchanges between these pools and the atmosphere. Thus, because these pools were increasing in size in Canada and the US, the sink strength for European forests is probably underestimated by this analysis and by Kauppi et al. (1992). Uptake of carbon by living biomass was added to the diagram using the net increment in European growing stocks (576×10^6 m^3) reported by the ECE/FAO (1992). This increment in stemwood and bark was converted to carbon (115 TgC) using an average wood density of 0.4 t biomass m^{-3} and a carbon content of 50% (Kauppi et al., 1992). The increment in stemwood was converted to an increment in total biomass (200 Tg) assuming a mid-value expansion factor of 1.75. Kauppi et al. (1992) cited a range of 1.4 to 2.1.

In the analysis of the former USSR by Kolchugina and Vinson (1993), the net increment of 557 TgC in biomass is an estimate of growth minus losses to fire. It seems not to account for the losses of biomass to products and slash. Assuming that the ratio of increment/emissions for wood products in the former Soviet Union is the same as it is for Canadian forests, 88 Tg may have been transferred from biomass to products, and 42 Tg may have accumulated annually in products. Similarly, the amount of biomass annually transferred to slash (91 TgC) and the annual accumulation in slash (82 TgC) were calculated from the emissions from slash on the basis of ratios obtained from US forests (Turner et al., 1995) (Fig. 3). These assumptions reduce the change in biomass from 557 TgC to 378 TgC (557–88–91); they increase the accumulation in products from 0 to 46 TgC; and they increase the accumulation in slash from 0 to 82 TgC. The total net accumulation is not affected.

Summing the modified budgets for Canada, the conterminous US, Europe, and the former USSR gives the values shown in Fig. 6. The forests (and products) are a net sink of about 820 TgC yr^{-1}. More than half of the increment is in biomass (500 TgC yr^{-1}). Products, slash, and soils (excluding peatlands) are accumulating 140, 80, and 80 TgC, respectively. Another 20 TgC are accumulating in peat.

Comparison of Fig. 6 with Fig. 1 shows what fraction of these sinks can be explained on the basis of land-use change (largely harvests). Corresponding values for the annual increment in

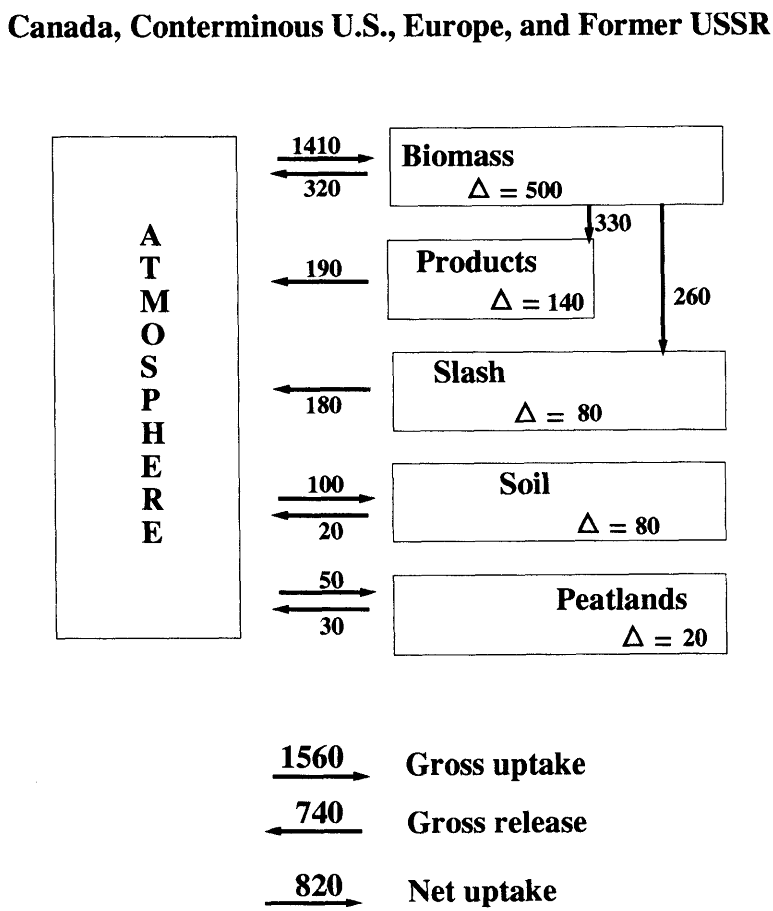

Fig. 6. Changes in the major pools of carbon in Canadian, conterminous US, European, and former USSR forests, and annual exchanges of carbon between these pools and the atmosphere (modified from analyses by Kauppi et al., 1992; Kolchugina and Vinson, 1993; Apps and Kurz, 1994; and Turner et al., 1995).

products are reasonably close: 140 TgC from forest inventories, and 160 TgC from land-use change. Values for the accumulation of slash are also in reasonable agreement, 80 and 90 TgC, respectively, when the 55 Tg increment in Canadian forest soils is assumed to be an increase in slash. The fact that the approaches agree in these components is satisfying because both components are the result of land use.

For soils, the agreement is poorer: a net uptake of 80 TgC according to analyses based on forest inventories, and a net release of 60 TgC calculated from changes in land use. The accumulation of 50 TgC in peatlands is clearly unrelated to land-use change, although the release of 30 Tg resulted from the use of peat for fuel (Kolchugina and Vinson 1993).

The largest difference between the results of the two approaches is for biomass, the component that is determined by different methods. Data from forest inventories show a net increment of 500 TgC in biomass, while estimates based on land-use change show a net loss of 220 TgC. The absolute difference is 720 TgC.

Regrowth of biomass (the flux of carbon from the atmosphere to biomass) from previous logging and abandonment (670 TgC yr^{-1}) (Fig. 1) accounts for only about half of the growth in biomass observed in forest inventories (1410 TgC yr^{-1}) (Fig. 6).

It is important to recall that the major difference between approaches is the ways in which changes in living biomass are determined. Changes in all other components (products, slash, soil) are based on models that simulate rates of production and oxidation. In his respect, the two approaches are not different.

2.4. *Implications*

The finding that analyses based on forest inventories show an annual net accumulation in northern temperate zone and boreal forests that is 0.8 PgC greater than that found in analyses based on land-use change is different from the argument advanced recently by Houghton (1993, 1995a, 1995b). In these earlier analyses Houghton observed that the rate of accumulation of carbon in forests recovering from logging was similar to the rates of accumulation measured by forest inventories. Because the rates were similar, Houghton argued that land-use change accounted for the observed sink, and hence that additional carbon (missing carbon) was not likely to be found in the vegetation of these forests. Houghton's comparison, however, was of growth in biomass (gross uptake) (670 TgC in Fig. 1) with net accumulation in biomass (500 TgC in Fig. 6). The diagrams used throughout this paper (Figs. 1–6) help make clear that the appropriate comparisons are between either 670 and 1410 TgC or −220 and +500 TgC.

The finding of a net uptake by mid-latitude forests is similar to that reported by Dixon et al. (1994). If the findings are correct, the imbalance in the global carbon equation (1) is somewhat smaller than reported in the IPCC 1994 scientific assessment (Schimel et al., 1995); that is, 1.1 rather than 1.4 PgC yr^{-1}. The difference is within the estimated error. However, the imbalance of 1.1 PgC yr^{-1} for the 1980s seems unlikely to be explained by the accumulations of carbon in forests of the northern mid-latitudes, unless the forest inventories have systematically underestimated growth in one or more of the pools.

From another perspective, one in which the global carbon imbalance is defined on the basis of emissions from land-use change alone (1.6 PgC yr^{-1}), the accumulation observed in forest inventories accounts for half of that imbalance.

The difference of 0.8 PgC yr^{-1} between the two types of analyses suggests that processes other than land-use change are important in accumulating carbon in these mid-latitude forests. An additional amount of carbon might be accumulating either in terrestrial ecosystems that are not affected by land-use change, or in disturbed ecosystems that are not adequately understood; that is, in ecosystems that are recovering from human disturbance more rapidly than expected. King et al. (1995) recently investigated this latter possibility. They allowed forests recovering from logging and abandonment to accumulate carbon at a rate that varied with the CO_2 concentration of the atmosphere. The experiment did not help resolve the difference between modeled and observed CO_2 concentrations, and King et al. concluded that CO_2 fertilization cannot be a major explanation for the imbalance in the modeled carbon cycle.

Other possibilities for an increased storage of carbon on land include the mobilization of fixed nitrogen as a result of human activities (Galloway et al., 1995); variations in radiation (cloud cover), surface temperature and moisture (Dai and Fung, 1993; Grace et al., 1995); and past natural disturbances (fire, insects, disease) that may have affected the age structure of forests in such a way as to create rapidly growing forests at present (Kurz et al., 1995). Analyses based on forest inventories have taken such historical patterns into account in temperate zone and boreal regions. The possibility remains that tropical forests, where inventories are almost non-existent, might be accumulating carbon more rapidly than expected on the basis of land-use change. The recent measurement of a net uptake of CO_2 in an undisturbed tropical forest in the Amazon supports this possibility (Grace et al., 1995).

3. Tropical forests

3.1. *Estimates of flux*

Estimates of the release of carbon from tropical forests are in agreement (Table 1) because they are based on essentially the same study (Houghton and Hackler, 1995). Other estimates for the tropics include a range between 0.6 and 1.6 PgC yr^{-1} (Hall and Uhlig, 1991). The difference between the high and low estimates of Hall and Uhlig (1991) result largely from different estimates of biomass. For their low estimate of flux, Hall and Uhlig (1991) used estimates of biomass from Brown et al. (1989) that were obtained from the FAO/UNEP (1981) assessment of tropical forests in 1980. The biomass of tropical forests has declined, however, over the past decades (perhaps centuries) as a result of selective logging, shifting cultivation, fuelwood removals, and other processes (FAO, 1993; Uhl and Vieira, 1989; Woods, 1989; Gajaseni and Jordan, 1990). Thus the use of current (low) estimates of biomass is inappropriate for past fluxes.

The current (low) estimates of biomass also underestimate the current release of carbon if the calculations are based on changes during a single year. Most of the carbon released in 1980, for example, was from lands cleared and products harvested in the years before 1980. The delayed fluxes result from oxidation of wood products, slash, and soil carbon. Delays are also associated with the accumulation of carbon in regrowing forests logged in previous years.

Current (low) estimates of biomass also underestimate the release of carbon if the calculations are based on deforestation alone and do not include processes such as logging and shifting cultivation that reduce the biomass of forests. In peninsular Malaysia, for example, the loss of forest area between 1972 and 1982 was 18% while the loss in biomass during the same interval was 28% (Brown et al., 1994). For all of tropical Asia over the period 1880–1980, the loss of carbon attributable to deforestation was only 57% of the total loss (Flint and Richards, 1994). The other 43% was from reductions in the biomass of the forests remaining.

Although Hall and Uhlig (1991) included logging and shifting cultivation in their simulations, the loss of carbon attributed to these activities was small relative to the reductions in biomass reported elsewhere (Brown et al., 1994; Flint and Richards, 1994). Actual logging rates may be significantly higher than those reported in official statistics (and used in calculations of flux) because much of the logging is illegal (Brown et al., 1994).

3.2. *Geographical distribution of the net flux of carbon from terrestrial ecosystems*

Tropical deforestation is distributed almost evenly about the equator. Table 2 shows the N:S distribution of deforestation to have been about 46:54 for the decade of the 1980s. The N:S distribution of deforestation for countries straddling the equator was assumed in this estimate to be in proportion to the N:S distribution of total area. In tropical Asia almost 75% of deforestation was in the northern tropics, but in tropical America only about 30% of the deforestation occurred in countries north of the equator. Earlier estimates of the distribution, based on the flux itself rather than on rates of deforestation, show distributions of 59:41 (Houghton et al., 1987) and 48:52 (Houghton, 1991), based on rates of deforestation reported for the late 1970s (FAO/UNEP, 1981) and late 1980s (Myers, 1991), respectively.

The recent analysis by Ciais et al. (1995), based on atmospheric data and modelling, found that in 1992 the source of carbon to the atmosphere from terrestrial ecosystems in the tropics was 1.7 PgC. Perhaps fortuitously, the net flux calculated on the basis of land-use change in 1990 was identical (Table 3). However, Ciais et al. (1995) found that the northern tropics were a source of carbon and the southern tropics, a sink, a finding that is very different from the N-S distribution expected on the basis of the distribution of deforestation, the dominant change in land use.

The difference may be fortuitous. The year 1992 was atypical for the decade of the 1980s in that the growth rate of atmospheric CO_2 was low: 1.2 PgC rather than the average of 3.2 PgC yr^{-1} for the 1980s (Conway et al., 1994), suggesting a global sink 2 PgC greater than observed during the 1980s. (In this context, it is interesting to note the difference between the mid-latitude terrestrial sink determined by Ciais et al. (1995) (3.5 PgC) for 1992 and the average uptake found by forest inventories in the 1980s (0.8 PgC) (Table 3).). The release of carbon calculated for deforestation is not specific for 1992. Although fluxes are calculated annually, the rates of land-use change used in the analysis are generally averaged over periods of 5–10 years, longer for the years prior to 1950 (Houghton and Hackler, 1995), and thus do not capture year-to-year differences in rates of deforestation. Annual variability in the rates is not thought to be large for the tropics as a whole, but in the Brazilian Amazon the rate decreased from an average of 2.2×10^6 ha yr^{-1} between 1978 and 1988 to 1.1×10^6 ha in 1990–1991 (Fearnside,

Table 2. *Average rates of deforestation (in 10^3 ha yr^{-1}) in tropical countries north and south of the equator (FAO 1993)*

	0°–30°N	0°–30°S	Total
Africa			
Sahelian Africa	890		
West Africa	591		
Cameroon	122		
Central African Republic	129		
Equatorial Guinea	7		
Congo	16	16	
Gabon	58	58	
Zaire	244	488	
Tropical Southern Africa		1345	
Madagascar		135	
total Africa	2057(50%)	2042(50%)	4100
Asia			
South Asia	551		
Continental Southeast Asia	1314		
Malaysia	396		
Philippines	316		
Indonesia	305	909	
Papua New Guinea		113	
total Asia	2882(74%)	1022(26%)	3904
Latin America			
Central America	1112		
Caribbean	122		
Colombia	367		
Venezuela	599		
Bolivia		625	
Brazil		3671	
Ecuador		238	
Paraguay		403	
Peru		271	
total Latin America	2200(30%)	5208(70%)	7408
total all tropics	7139(46%)	8272(54%)	15,411

1993). Over the decade of the 1980s the total rate for the entire tropics increased by less than 40% (FAO 1993). Short-term variations could be determined with high-resolution data from satellite, but a global, or even tropics-wide, investigation of annual deforestation rates has not been undertaken.

A comparison of the geochemical approach (Ciais et al. 1995) with results based on data from terrestrial ecosystems is difficult to interpret (Table 3). The flux determined from variations in the concentration and isotopic composition of CO_2 is based on a single year, atypical from the perspective of the global carbon cycle, and the flux based on land-use change is a running average over several years. The fact that both methods find a source of 1.7 PgC yr^{-1} for the tropics is interesting, but the different N-S distributions of the flux only raise questions. The differences suggest that year-to-year variations in temperature

Table 3. *Terrestrial fluxes of carbon calculated from deconvolution of atmospheric data (Ciais et al., 1995), from changes in land use (Houghton and Hackler 1995), and from forest inventories (Kauppi et al., 1992; Kolchugina and Vinson, 1993; Apps and Kurz, 1994; Turner et al., 1995) (units are PgC yr^{-1})*

Latitudes Years	Net terrestrial flux (PgC) (Ciais et al., 1995) 1992	Flux from land-use change (Houghton and Hackler, 1995) Around 1990	Flux calculated with data from forest inventories 1980s
30°–60°N	−3.5(±0.9)	0.0(±0.5)	−0.8
30°S–30°N	1.7(±1.6)	1.7(±0.7)	–
0°–30°N	2.0(±1.3)	0.8(±0.5)	–
0°–30°S	−0.3(±1.0)	0.9(±0.5)	–
global	−1.8	1.7(±0.7)	–

and, perhaps, precipitation (Grace et al., 1995; Keeling et al., 1995) have large effects on terrestrial fluxes of carbon.

4. Conclusions

According to analyses based on data from forest inventories, the accumulation of carbon in forests of the northern mid-latitudes is 0.8 PgC yr^{-1}. According to analyses based on changes in land use, the net accumulation is zero. The component accounting for the largest difference (biomass) is that component that is independently determined by the two methods. The changes in biomass estimated by the two approaches differ by 0.72 PgC yr^{-1}.

If both approaches are accurate, the imbalance in the global carbon budget is less than suggested by earlier analyses (Houghton, 1995b; Schimel et al., 1995). A revised budget is as follows:

$$\begin{array}{ccccc} \text{atmospheric increase} & = & \text{fossil fuel} & + & \text{land-use change} \\ 3.2(\pm 0.2) & = & 5.5(\pm 0.5) & + & 1.6(\pm 0.5) \\ -\,\text{ocean} & - & \text{uptake by northern forests} & - & \text{residual sink} \\ -2.0(\pm 0.8) & - & 0.8(\pm 0.4) & & -1.1(\pm 1.1) \end{array} \quad (2)$$

If the approach based on data from forest inventories is accurate, the global imbalance is unlikely to be found in northern mid-latitude forests. The data from forest inventories would have to be systematically low. The emphasis of forest inventories is on biomass, however. Changes in soil carbon are calculated rather than measured, and it is possible that carbon is accumulating in soils more rapidly than expected. The factors responsible for the difference between the observed and calculated accumulation of biomass in mid-latitude forests raises the question of whether the same factors might also be important in accumulating carbon in non-forest ecosystems of the mid-latitudes or in tropical forests, compensating to some extent for the emissions estimated from changes in land use there.

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