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The annual net flux of carbon to the atmosphere from changes in land use 1850–1990*

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ABSTRACT

Rates of land-use change, including clearing for agriculture and harvest of wood, were reconstructed from statistical and historic documents for 9 world regions and used, along with the per ha changes in vegetation and soil that result from land management, to calculate the annual flux of carbon between land and atmosphere. Between 1850 and 1990, changes in land use are calculated to have added 124 PgC to the atmosphere, about half as much as released from combustion of fossil fuels over this period. About 108 PgC are estimated to have been transferred from forests to the atmosphere as a result of human activity, 2/3 from tropical forests and 1/3 from temperate zone and boreal forests. Another 16 PgC were lost from non-forests, largely as a result of cultivation of mid-latitude grassland soils. About 800×10^6 ha of forest were cleared for agricultural purposes, and approximately 2000×10^6 ha were harvested. Conversion of forests to agricultural lands released 105 PgC; harvest of wood released about 20 PgC. These estimates of release include the accumulations of carbon in wood products (17 PgC) and woody debris (4 PgC), the losses of carbon from oxidation of wood products, woody debris, and soil organic matter (373 PgC in total), and the accumulations of carbon in forests recovering from harvest and in the fallows of shifting cultivation (249 PgC). Over the decade of the 1980s the annual net flux of carbon from changes in land use averaged about 2.0 PgC yr^{-1}, higher than the 1.6 PgC yr^{-1} estimated previously. Almost all of this flux was from tropical regions, where rates of deforestation averaged approximately 15×10^6 ha yr^{-1}. Outside the tropics, regrowth of forests logged in earlier years largely balanced the losses of carbon from oxidation of wood products.

1. Introduction

The rôle of terrestrial ecosystems in the global carbon budget is uncertain. Analyses based on changes in land use show an average global source of about 1.6 PgC yr^{-1} for the 1980s (Houghton and Hackler, 1995), while analyses based on atmospheric and oceanic data and models show a terrestrial sink of 2–3.4 PgC yr^{-1} (Tans et al., 1990; Enting et al., 1995; Francey et al., 1995; Keeling et al., 1995; Rayner et al., 1999). At least part of the difference between the two approaches may be explained by the fact that the net flux of carbon between terrestrial ecosystems and the atmosphere results from two independent processes: direct human activity (deliberate) and either natural causes or indirect human activity (inadvertent). Deliberate effects include changes in land use, harvest of wood, and other human-induced modification of the land surface. Inadvertent effects include those associated with natural disturbances, elevated CO_2, nitrogen deposition, and climatic change. Distinguishing between the two effects is important for both political and scientific reasons. The distinction is important politically because the emissions of carbon from deliberate human activities can be managed. For example, the nations of the world can collectively reduce emissions of CO_2, whereas inadvertent emissions are more difficult to manage. Scientifically, the

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distinction is important because global changes in terrestrial carbon resulting from land management are more readily determined and identified than changes resulting from other factors, and thus they help constrain the residual flux of carbon resulting from inadvertent effects.

Most analyses of the global carbon budget based on atmospheric data do not distinguish between deliberate and inadvertent changes in terrestrial carbon storage. These analyses, as well as those based on the data from forest inventories (Houghton, 1996, 1998), calculate a total net terrestrial flux. Analyses based on ecological data and models, in contrast, have generally considered either deliberate or inadvertent effects, but not both. On the one hand, analyses based on changes in land use have, of course, considered deliberate changes. On the other hand, terrestrial ecosystem models used to explore possible mechanisms for the accumulation of carbon on land have generally considered only the inadvertent effects of elevated CO_2 (McGuire et al., 1997), N deposition (Holland et al., 1997), climate (Dai and Fung, 1993), or some combination of the three factors (VEMAP, 1995) on terrestrial carbon storage.

The purpose of this paper is to present an estimate of annual changes in terrestrial carbon storage that result from deliberate management of the land surface. Land-use change is defined here as deliberate human activity for the purpose of managing terrestrial ecosystems. Clearing forests for agricultural lands and harvesting wood are the major contributors to land-use change. These activities are relatively well documented through time. In contrast, the accumulation or loss of carbon in ecosystems undisturbed by, or remote from, human activities is rarely measured and difficult to determine except indirectly. Thus, although the flux of carbon from land-use change may not be the total net flux of carbon from terrestrial ecosystems, it is, nevertheless, obtainable from existing data, and it provides a constraint on the residual terrestrial flux that is inadvertent, or attributed to non-anthropogenic factors.

2. Methods

2.1. *Overview of the approach*

The method used to calculate emissions (and accumulations) of carbon from land, as a result of land-use change, has been described previously (Houghton et al., 1983, 1987; Houghton and Hackler, 1995). The accounting procedure is based on the fact that most uses of land affect the amount of carbon held in vegetation and soil. Human activities that reduce the area of forests release carbon to the atmosphere as a result of burning and decay; activities that increase the area of forests withdraw carbon from the atmosphere as a result of forest growth. More subtle changes within forests also affect the storage of carbon in biomass. Harvest of wood followed by regrowth of the forest may not affect the area of forest but will modify, at least temporarily, the storage of carbon in the forest and in wood products.

The approach used here to calculate change was based on two types of data. First, annual rates of land-use change (expansion and contraction of agricultural area (ha yr^{-1}), including croplands, pastures, and shifting cultivation, and rates of wood harvest (m^3 yr^{-1})) were used to determine the areal extent and the types of ecosystems affected by different land uses. Second, the per ha changes in carbon associated with these changes in land use formed the basis for response curves that were used in a model to calculate annual changes in C ha^{-1} that follow management or a change in land use.

The approach accounts for all of the carbon on an affected unit of land: live vegetation, soil, woody debris generated at the time of disturbance (slash), and wood products. The fate of each of these components was tracked in a bookkeeping model. The losses and accumulations of carbon following an initial change in land use occur over years to decades, as dead material decays and as forests regrow following harvest. These time lags were included in the analysis. We emphasize that the analysis included the accumulations of carbon that result from recovery or regrowth as well as the releases that result from decay and oxidation. In this sense the flux is a *net* flux, although it is only the net flux from land-use change (deliberate changes in land use).

Some changes in terrestrial ecosystems were *not* addressed in these analyses of land-use change. Ecosystems that were not directly affected by land use were not considered in the analysis. Natural disturbances were ignored. Furthermore, rates of carbon accumulation in forests recovering from harvest did not vary through time as a result of temporal variations in environmental factors, such as CO_2, nitrogen deposition, acid precipitation, UV-B, or climate. For a given ecosystem, rates of forest growth were the same in 1980 as in 1850. Thus the calculated flux of carbon includes only those changes in carbon that were associated with land-use change. The analysis did not include all anthropogenic effects, however. For example, fire suppression and silvicultural practices were not included.

2.2. *Data*

Historical rates of land-use change and the ecosystems affected by those changes have been reconstructed through a series of analyses, the earliest of which was described by Houghton et al. (1983) and Woodwell et al. (1983). For many regions (North America, Europe, China, Pacific developed, and North Africa and the Middle East) the data on land use have been revised little, although they have been extended here from 1980 to 1990. Other regions have been reanalyzed and the rates of land-use change have been extensively revised. Revised data for the former Soviet Union, for Latin America, and for tropical Asia are described in Melillo et al. (1988), Houghton et al. (1991a, b), and this paper, respectively.

The data and sources used for the calculation of flux presented here are largely the same as documented in Houghton and Hackler (1995). Here we extend the analysis of the temperate and boreal zones to 1990 and include a revision for tropical Asia. The revised data are available in a numerical data package from the Carbon Dioxide Information and Analysis Center (Houghton and Hackler, 1999). They are summarized below in figures and as qualitative trends. The data are of two kinds, either related to rates of land-use change or to per ha changes in carbon storage following disturbance and management.

2.2.1. Data on land use. For this analysis the world was divided into nine geopolitical regions. The major changes in land use between 1850 and 1990 are summarized below for each region. In general, the analysis included the clearing of natural ecosystems for croplands and pastures; the abandonment of cleared lands, followed by recovery of the original vegetation and soils; and the harvest of wood from forests, followed by regrowth of the forest. In most regions harvest of industrial wood (timber) was distinguished from harvest of fuelwood. In Latin America and tropical Asia, shifting cultivation was also included.

North America. For most of the period 1850 to 1970, the areas of croplands in the US and Canada were obtained from the US Bureau of the Census (1977) and Urquhart (1965), respectively. For more recent years cropland area was assumed to be equivalent to arable land (FAO, 1992), although the FAO definition of arable land also includes temporary pastures. Changes in the area of pastures were assumed to replace natural grasslands and did not affect carbon storage. Increases in croplands were divided among 5 types of ecosystems in North America (Table 1): boreal forests, temperate evergreen forests, temperate deciduous forests, woodlands, and grasslands. The type of ecosystem converted to cropland was determined from comparison of agricultural maps with maps of natural vegetation.

The amount of industrial wood and fuelwood removed from Canadian forests was obtained from volumes of the Census of Canada (1870–1921) and FAO (1953, 1946–1992). For the US the data were obtained from Reynolds and Pierson (1942), Clawson (1979), and FAO (1946–1992).

Former Soviet Union. The analysis of the former Soviet Union was described by Melillo et al. (1988). Three types of ecosystems were considered in both the western and eastern parts of the country: boreal forest, temperate deciduous forest, and grassland. The western and eastern parts of the region are divided by the Ural Mountains.

Historical areas in Soviet agriculture were obtained from Yatsunskiy (1982a, b) and the National Economy of the USSR (1959–1981). The ecosystems cleared were determined from comparison of maps of agricultural area and natural vegetation. Rates of wood harvest were obtained from Blandon (1983), Tseplyaev (1965), and FAO (1946–1992). Average rates of wood removal per ha were obtained from sources listed in Melillo et al. (1988). The effects of grazing and peat drainage were not considered.

Europe. Changes in the area of cropland in Europe before 1950 were obtained from Robertson (1956). After 1950, data were taken from FAO (1949–1992). Data for wood harvest were obtained from FAO (1953, 1965, and 1946–1992). Earlier rates of harvest were estimated on the basis of

Table 1. *Ecosystems included in each region, average carbon content of vegetation and soil, decay constant for dead plant material, and time required for harvested forests or abandoned agricultural lands to regain the carbon content of undisturbed ecosystems*

	Carbon in vegetation ($MgC\ ha^{-1}$)		Carbon in soil ($MgC\ ha^{-1}$)		Decay constant (yr^{-1})	Time for recovery of vegetation and soil (years)
	undisturbed	crops	undisturbed	cultivated		
North America						
boreal forest	90	5	206	155	0.03	50
temperate evergreen forest	160	5	134	101	0.05	50
temperate deciduous forest	135	5	134	101	0.05	50
woodland	27	5	69	34	0.4	50
grassland	7	3	189	142	0.3	10
Europe						
boreal forest	90	5	206	155	0.03	50
temperate evergreen forest	160	5	134	101	0.05	50
temperate deciduous forest	135	5	134	101	0.05	50
grassland	7	3	189	142	0.3	10
USSR						
boreal forest	90	5	206	165	0.05	80
temperate deciduous forest	135	5	134	107	0.04	40
temperate grassland	10	5	189	151	0.5	10
China						
tropical moist forest	250	5	120	84	0.5	37
temperate evergreen forest	160	5	134	101	0.05	50
temperate deciduous forest	135	5	134	101	0.05	50
grassland	7	3	189	142	0.3	10
Pacific developed						
tropical moist forest	250	5	120	84	0.5	37
temperate evergreen forest	160	5	134	101	0.05	50
temperate deciduous forest	135	5	134	101	0.05	50
woodland	27	5	69	34	0.4	50
grassland	7	3	189	142	0.3	10
North Africa and the Middle East						
tropical moist forest	250	5	120	84	0.5	37
temperate evergreen forest	160	5	134	101	0.05	50
grassland	7	3	189	142	0.3	10
desert scrub	3	1	58	87	0.3	10
Latin America						
tropical equatorial forest	200	5	98	74	0.5	40
tropical seasonal forest	140	5	98	74	0.4	35
warm coniferous forest	168	5	134	100	0.3	42
temperate broadleaved forest	100	5	134	100	0.5	25
tropical woodland	55	5	69	52	0.3	18
grassland	10	5	42	32	0.4	2
desert scrub	6	5	58	44	0.3	1
Sub-Saharan Africa						
closed forest	136	15	100	80	0.5	29
open forest	30	15	50	40	0.3	29
Tropical Asia						
tropical moist forest	250	5	120	84	0.5	37
tropical seasonal forest	150	5	80	56	0.4	29
woodland	60	5	50	37	0.3	12
grassland	60	5	50	50	0.3	12

population (McEvedy and Jones, 1978) and the 1923 per capita harvest of wood (Zon and Sparhawk, 1923).

China. The area of cropland in China was obtained from Grigg (1974) and FAO (1949–1992). Pastures were assumed to come from grasslands and to involve no change in carbon. Harvest of wood was determined from FAO (1946–1992). Before 1946, values for wood harvest were estimated on the basis of population (McEvedy and Jones, 1978) and the 1946 per capita harvest of wood. Rates of afforestation were estimated in recent decades from changes in the area of forests and woodlands (FAO, 1949–1992).

Pacific developed. The area of cropland was obtained from the International Institute of Agriculture (1922, 1939), Robertson (1956), Grigg (1974), and FAO (1949–1992). Harvest of wood was determined from Zon and Sparhawk (1923) and FAO (1965, 1946–1992). Before 1920, values for wood harvest were estimated on the basis of population (McEvedy and Jones, 1978) and the 1923 per capita harvest of wood (Zon and Sparhawk, 1923).

North Africa and the Middle East. After 1950 the area in cropland was obtained from FAO (1949–1992); before 1950 it was estimated assuming a constant (1950) area of cropland per capita with population data from McEvedy and Jones (1978). Industrial wood harvest was determined from FAO (1946–1992). Fuelwood was estimated from per capita use (Arnold and Jongma, 1978; Persson, 1974; Zon and Sparhawk, 1923; FAO, 1946–1992) with population estimates from McEvedy and Jones (1978).

Latin America. The analysis of land-use change in Latin America was described by Houghton et al. (1991a). The region was divided into seven ecosystems (Table 1). In addition to changes in agricultural area (both croplands and pastures) and harvest of wood (both industrial and fuelwood), the analysis considered shifting cultivation, afforestation, and the loss of agricultural land to degraded lands not readily recovering to forest. The increase in degraded lands was uncertain and has been omitted from the analysis reported here. Thus the net flux of carbon from this region is less than estimated originally by Houghton et al. (1991b).

Tropical Asia. The analysis of land-use change in tropical Asia is new. The analysis considered only three natural ecosystems: tropical moist forest, tropical seasonal forest, and tropical dry forest. Changes in the area of croplands were calculated from Bhattacharjee (1958), Grigg (1974), FAO (1992, 1998), and from references cited in Palm et al. (1986). Rates of forest clearing for shifting cultivation were obtained from FAO/UNEP (1981) for the 1970s and extrapolated backward in time on the basis of population (McEvedy and Jones, 1978). Recent estimates of deforestation were obtained from FAO (1997).

Annual harvest of industrial wood ($m^3\ yr^{-1}$) was obtained from Zon and Sparhawk (1923) and FAO (1992, 1998). The amount of industrial wood removed per ha was obtained from FAO (1993) and converted from $m^3\ ha^{-1}$ to $MgC\ ha^{-1}$ assuming a wood density of $0.34\ m^3\ ha^{-1}$ and a carbon content of 50%. Total removals and removals per ha, together, defined the area harvested. According to FAO (1993), between one-tenth and one-third of the aboveground biomass is damaged or killed during felling, and an additional one-tenth to one-third or more is killed in skidding. Thus between 20% and 67% of aboveground biomass is damaged. Assuming an additional 20% is left dead in belowground biomass, total damage is between 24% and 80%. We assumed that half of the initial biomass was killed in the process of logging. As in other regions, dead plant material decayed exponentially (Table 1). Ten, 10, and 80% of the industrial wood harvested decayed with rate constants of $1.0\ yr^{-1}$, $0.1\ yr^{-1}$, and $0.01\ yr^{-1}$, respectively.

For the years 1980 to 1995, rates of fuelwood and charcoal production were obtained from FAO (1997). Per capital use in 1980 (about $0.40\ m^3$ per capita) was calculated from population data (FAO, 1998), and assumed to apply to the years before 1980 based on population data from McEvedy and Jones (1976). The per capita rate is consistent with the country-specific rates reported by FAO (1992), that vary from a low of 0.18 and $0.27\ m^3$ per capita in Pakistan and India, respectively, to a high of $0.76\ m^3$ per capita in Indonesia and Laos. The assumption that a constant ratio applied in the past is probably not valid. Flint and Richards (1994) found the rate to vary inversely with population density, implying that the extraction of fuelwood in the early part of this analysis may have been underestimated. The distribution of fuelwood among forest types was based on the forest types dominant in each country. Fuelwood was generally harvested from secondary forests that had approximately 70% of the biomass of primary forests (FAO/UNEP, 1981). Removal rates were 25, 15, and 2 MgC ha^{-1} for the moist, seasonal, and dry forest types, and the harvested forests were eligible for reharvest (that is, they had reached 70% of primary forest biomass) after 8, 5, and 2 years. Ninety and 10% of the fuelwood harvested decayed with rate constants of 1.0 yr^{-1} and 0.1 yr^{-1}, respectively. The small fraction assigned to the 0.1 yr^{-1} rate represented those products used for local construction and tools.

Sub-Saharan Africa. Before 1950 the area of cropland was estimated by assuming a constant (1950) per capita area of cropland with population data from McEvedy and Jones (1978). After 1950 the cropland area was obtained from FAO (1949–1992). For the 1970s and 1980s, rates of deforestation were obtained from FAO's tropical forest assessments (FAO/UNEP, 1981; FAO, 1993). Neither shifting cultivation nor harvest of wood was included in the analysis of Africa.

2.2.2. Data on carbon. Vegetation. The amount of carbon per hectare in the live vegetation of different ecosystems ranged over two orders of magnitude from 200–250 MgC ha^{-1} for tropical moist forests to 3–6 MgC ha^{-1} for desert scrub (Table 1). Tropical forests with a dry season were of intermediate biomass (140–150 MgC ha^{-1}), as were forests of the temperate zone (135–160 MgC ha^{-1}). Boreal forests were of lower biomass (90 MgC ha^{-1}), followed by woodlands (27–55 MgC ha^{-1}), grasslands (7–10 MgC ha^{-1}), and desert scrub (3–6 MgC ha^{-1}). These average values include both above- and below-ground live biomass of trees as well as ground cover. The values were obtained from summaries of global vegetation (Whittaker and Likens, 1973; Ajtay et al., 1979; Olson et al., 1983) as well as from regional studies (for additional sources see Melillo et al., 1988; Houghton et al., 1991a,b; Houghton and Hackler, 1994, 1995).

Following a change of land use, the initial live vegetation was partitioned among three categories: live vegetation left standing, dead material left on site (slash = roots and stumps as well as the upper part of the bole, branches, twigs, and foliage), and woody material removed from the site (wood products). The partitioning of biomass among these pools varied with the ecosystem and the type of land-use change. The values for partitioning were determined from the forestry, ecological, and anthropological literature. Historical changes in the efficiency of harvests (that is, the amount of dead material left on site relative to initial biomass) are not well documented, although the exceptional study by Harmon et al. (1996) suggests that the amount of slash generated in the Pacific northwest has decreased by more than 25% over the last century. Less than 40% of the initial biomass has been stored in long-term products even in the most efficient harvests, and in much of the tropics harvests are less efficient.

The biomass of live vegetation in croplands and pastures was generally 5 MgC ha^{-1}. In African agriculture the value was 15 MgC ha^{-1}. The biomass of live vegetation immediately after harvest of wood varied from 0 MgC ha^{-1} for clearcuts to values as high as 87% of the initial vegetation for selective harvests. If the harvested lands were not converted to agricultural lands, the forests grew back (biomass increased). Forests recovered to their initial biomass in 25–80 years (Table 1). Rates of carbon accumulation in biomass were constant over time within an ecosystem but varied among ecosystems as a function of climate. Degraded forests in tropical Asia had a live biomass 10–30% lower than undisturbed forests. The biomass of forests in the fallow portion of shifting cultivation increased to about 50% of the initial biomass; then the fallows were cleared again for the next cycle of shifting cultivation. Greater detail is available in Houghton and Hackler (1995).

Dead plant material remaining on site at the time of clearing or harvest (slash) decayed with a decay constant that varied from as low as 0.03 for boreal forests to as high as 0.5 for tropical moist forests and grasslands.

Wood removed from forests for wood products was divided among fuelwood (decay constant = 1 yr^{-1}), pulp and paper products (decay constant = 0.1 yr^{-1}), and sawn wood, plywood, panels, and lumber (decay constant = 0.01 yr^{-1}). The partitions were based on historical statistics for individual regions and countries before 1945, and on the annual forestry statistics of FAO (1946–1992) after 1945. With the burning associated with shifting cultivation, 2% of the biomass was transformed to elemental carbon (decay constant = 0.001 yr^{-1}).

Soil. The initial stocks of carbon in the surface meter of soil ranged from 206 MgC ha^{-1} for boreal forests to 32 MgC ha^{-1} for tropical grassland in Latin America. With cultivation, about 25% of this carbon was lost to the atmosphere (Detwiler, 1986; Schlesinger, 1986; Davidson and Ackermann, 1993). The rate of loss varied with the ecosystem. Most tropical forest soils reached a new steady state after 5 years; boreal forest soils required as long as 65 years of cultivation to reach the minimum carbon content. Grasslands converted to pastures neither lost nor gained soil carbon, as pasture soils are not generally cultivated. The loss of carbon from soils as a result of shifting cultivation was intermediate between the losses resulting from cultivation and grazing. Following the abandonment of cultivated lands, soil carbon levels returned to pre-disturbance conditions in the same amount of time the vegetation took to recover, usually 50 years but varying geographically as a function of climate.

2.3. *A model*

The bookkeeping model is a cohort or age-class model with an annual time step. The area of each ecosystem affected by land-use change was tracked for as long as the ecosystem (soil and vegetation) was either losing or gaining carbon. Ecosystems reaching a new steady state (either fully recovered or a minimum soil carbon content following cultivation) were removed from the cohort structure. They rejoined the pool of lands available for subsequent changes in land use.

The fraction of plant material assigned to slash was added to carbon pools that decayed at rates specific for each ecosystem. Similarly, the fractions of wood products with different average decay constants were added to their respective pools, specific for each region, ecosystem, and type of land-use. Each year the additions of slash and wood to these pools and the losses of carbon from the pools through decay were calculated. The pools themselves either increased or decreased in size as rates of harvest increased or decreased.

Lands abandoned from croplands or pastures, lands entering the shifting cultivation cycle, and lands harvested began to accumulate carbon in vegetation. The carbon content was defined for each year of recovery, and the changes from year-to-year determined the annual flux of carbon from the atmosphere to the ecosystem. A similar cohort structure applied to the soils of the ecosystems, except that in the years following the initiation of cultivation soils lost carbon. In the fallow period of shifting cultivation and after abandonment of croplands, soils accumulated carbon.

The structure of the model is most easily summarized as follows. In the year of land-use change, some of the carbon of live vegetation was burned and some was transferred to slash and wood products. In the next and subsequent years, carbon was transferred only between the following pools and the atmosphere: live vegetation gained carbon from the atmosphere during regrowth, soils lost or gained carbon depending on the time since disturbance, and the slash and product pools lost carbon to the atmosphere.

For each region, each type of ecosystem, and each type of land use the area, carbon content, and flux of carbon were calculated annually. The results are summarized below.

3. Results

3.1. *Changes in land use*

In the 140 years between 1850 and 1990, the area of cultivated lands, worldwide, is estimated to have increased by more than a factor of 4, from about 320×10^6 ha in 1850 to 1360×10^6 ha in 1990. Although some of this increase took place in the 19th century as a result of agricultural expansion in the US, Canada, and the former Soviet Union, the most rapid increase occurred in tropical regions after 1950 (Fig. 1). In recent years agricultural areas outside the tropics have increased only in North Africa and the Middle East and in the developed countries of the Pacific. Nevertheless, the global expansion of cultivated lands has accelerated; approximately half of the increase of 1000×10^6 ha occurred in the last 50 years.

The area of pastures and rangelands increased worldwide as well, but much of the increase (1500×10^6 ha) occurred on grasslands or other semi-arid areas. The conversion of these ecosystems to grazing lands was assumed here to

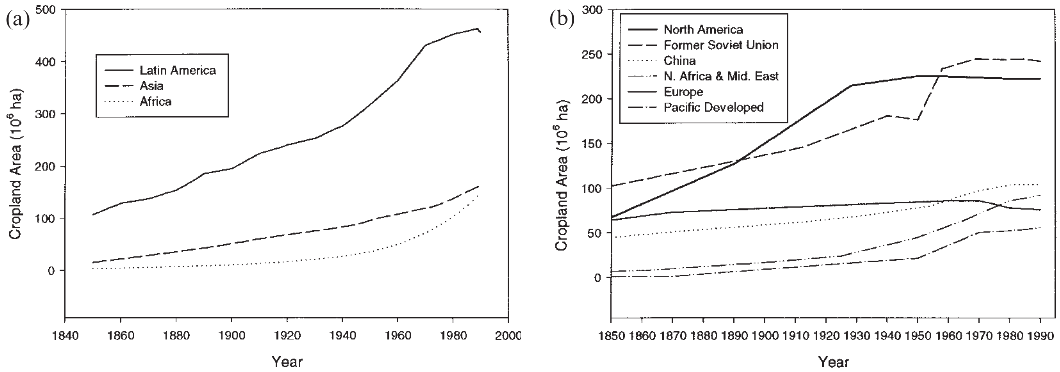

Fig. 1. Area of croplands: (a) tropical regions; (b) temperate zone regions.

have had no effect on carbon storage (either biomass or soil). On the other hand, approximately 180×10^6 ha of pastures were cleared from forests. Altogether, about 730×10^6 ha of croplands and pastures were cleared from forests and woodlands over the 140-year period, and almost 500×10^6 ha of grasslands and other non-forest ecosystems were converted to cultivated land. The increase in agricultural lands reduced the area of the world's forests by 17% since 1850, with most of the loss occurring in the tropics.

The area of forests harvested between 1850 and 1990 (about 2000×10^6 ha) was considerably larger than the area cleared for croplands and pastures. Many of the forests harvested remained as forests, however, and are accumulating carbon at present, so the relative areas affected by clearing and harvest do not reflect their relative effects on carbon storage.

Table 2. *Net flux of carbon to the atmosphere from changes in land use*

Region	Average annual flux 1980–1990 (PgC yr^{-1})	Total net flux 1850–1990 (PgC)
tropical Asia	1.08 ± 0.5	38.6
tropical America	0.55 ± 0.3	30.5
tropical Africa	0.29 ± 0.2	9.5
subtotal tropics	1.9 ± 0.6	79
North America	$0.00 + 0.2$	12.7
Europe	$-0.02 + 0.2$	4.9
Former Soviet Union	$0.03 + 0.2$	10.4
China	$0.06 + 0.2$	9.4
Pacific developed	$0.01 + 0.2$	4.1
North Africa and Middle East	$0.02 + 0.2$	3.1
subtotal non-tropics	0.1 ± 0.5	45
global total	2.0 ± 0.8	124

3.2. *Changes in carbon*

1850–1990. The total net flux of carbon to the atmosphere from changes in land use according to this analysis was 124 PgC over the period 1850 to 1990. Changes in and to forests accounted for almost 90% of the net long-term flux. Tropical Asia and Latin America contributed about half of the total (Table 2). The annual flux, globally, increased from about 0.4 PgC yr^{-1} in 1850 to 2.0 PgC yr^{-1} in 1990.

The most important land-use change was the expansion of agriculture. Croplands were responsible for about 68% of the total net flux, pastures (from forests) for 13%, and shifting cultivation for about 4% (Fig. 2). Harvest of wood accounted for 16% of the long-term flux, and the establishment of plantations removed carbon equivalent to 1% of the net flux. The annual flux attributable to harvest and regrowth was relatively constant despite a 5-fold increase in the rate of harvests over this period because the losses of carbon associated with the oxidation of slash and products were largely offset by the accumulation of carbon in regrowing forests. A constant rate of harvest would have yielded a net annual flux close to 0 PgC yr^{-1}, so the relatively constant release of about 0.2 PgC yr^{-1} indicates that rates of wood

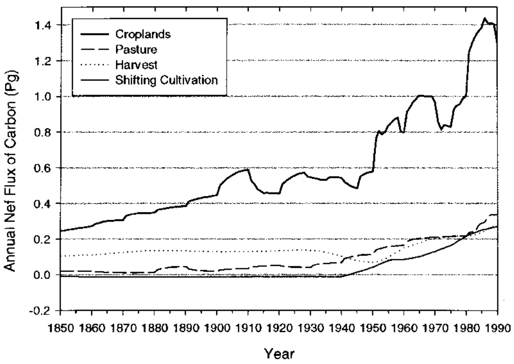

Fig. 2. Annual net flux of carbon to the atmosphere from major categories of land-use change.

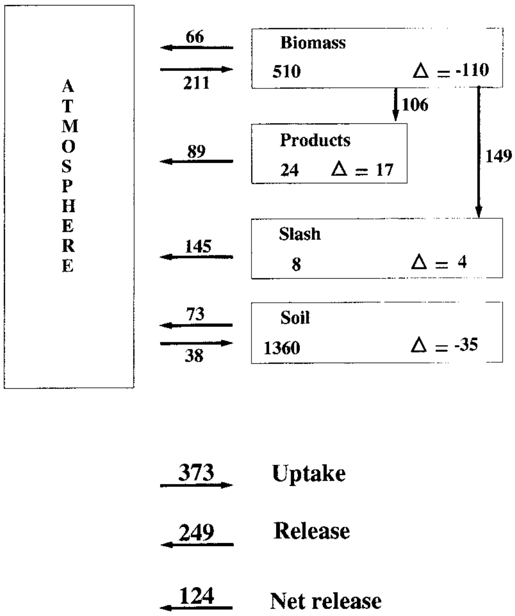

Fig. 3. Flows of carbon between the major components of terrestrial ecosystems and the atmosphere as a result of changes in land use over the 140-year period 1850–1990. The net flux is obtained either by summing the exchanges between the pools and the atmosphere or by summing the changes (deltas) in each pool. The value in the lower left of each box refers to the total amount of carbon (Pg) held in that pool in 1990. The uptake of carbon by live biomass and soils and the transfer of carbon from live biomass to products and slash are underestimated here because neither shifting cultivation nor harvest of wood was included in the analysis of tropical Africa.

harvest generally increased over time. The annual releases of carbon from harvests and shifting cultivation are likely to be underestimates here because neither type of land use was included in the analysis of tropical Africa.

The contribution of vegetation, wood products, slash, and soil to the net flux of 124 PgC is summarized in Fig. 3. Over the 140-year period live vegetation lost about 110 PgC, or 18% of the carbon in vegetation in 1850. This net loss from live vegetation included an uptake of 211 PgC in the regrowth of forests following harvests, shifting cultivation, and abandonment of agricultural lands. Losses of carbon from live vegetation included those resulting from burning (66 PgC) and the harvest of wood (106 PgC actually harvested and an additional 149 PgC of slash generated in the process). Soils lost 73 PgC as a result of cultivation and disturbance during harvests but gained 38 PgC in recovery, for a net loss of 35 PgC. This loss of carbon from soils is less than 3% of the carbon initially present in soils at the start of the period. Of the 106 PgC harvested in wood products, 89 PgC were subsequently oxidized (33 Pg as fuelwood and 56 Pg from decay of longer-lasting products), for an accumulation of 17 PgC in long-term storage. About 4 Pg of carbon also accumulated in slash (woody debris) on the forest floor, although the turnover time of this material is much shorter than it is for wood products. Over the entire period, gross emissions (373 Pg) and gross uptake (249 Pg) of carbon associated with land-use change were about 3 and 2 times higher than the net flux, respectively. These values underestimate the gross land-use exchanges of carbon somewhat because neither shifting cultivation nor wood harvest was included in the analysis of Africa.

The annual gross emissions (and uptake) of carbon from land-use change increased through time just as the net flux increased (Fig. 4). The ratio of gross to net emissions declined, however, from about 5 at the start of the 140-year period to about 3 by 1990. The decline resulted from the decreased importance of shifting cultivation and the increased importance of permanent cultivation in more recent times. Again, estimates of the gross land-use fluxes are low because of an incomplete analysis of harvests in Africa.

1980–1990. For the period 1980–1990 the net annual flux from changes in land use is estimated

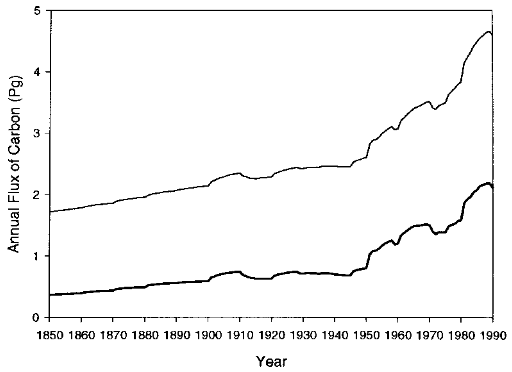

Fig. 4. Gross and net annual emissions of carbon from global land-use change (thin and thick lines, respectively). Gross emissions (and uptake) exceeded net emissions largely because of rotational forms of land use (shifting cultivation and harvest of wood followed by regrowth). Because these activities were not included in the analysis of tropical Africa, gross land-use emissions for Africa were estimated here with the assumption that the annual ratios of gross to net emissions in Africa were the same as the average determined for Latin America and tropical Asia.

here to have averaged 2.0 ($\pm$0.7) PgC yr^{-1}. The distribution of this flux among regions is shown in Fig. 5. In the 1980s almost the entire flux was from tropical lands (Table 2). Emissions from tropical Asia, Latin America, and sub-Saharan Africa accounted for approximately 54, 28, and 14% of global emissions, respectively. Outside the tropics the releases of carbon from oxidation of wood products were approximately balanced by the calculated uptake of carbon in forests regrowing from previous harvests. Only Europe showed a net accumulation of carbon in the 1980s. Recall that these calculated fluxes refer only to those changes in terrestrial carbon storage that have resulted from forestry and changes in land use, that is, deliberate activities. Other, non-anthropogenic or inadvertent processes may also have affected carbon stocks, but any such changes were ignored in this analysis.

4. Discussion

4.1. *Comparison with other analyses*

The estimated release of 124 PgC between 1850 and 1990 is lower than the earliest estimate of a terrestrial release of carbon (Houghton et al., 1983) but somewhat higher than the most recent estimate (Houghton and Hackler, 1995) (Fig. 6) (Table 3). The long-term flux is about 30% lower than the earlier estimate of Houghton et al. (1983) despite the fact that it applies to a period 20 years longer. The initial estimate of 180 PgC (Houghton et al., 1983) was an overestimate, first, because the

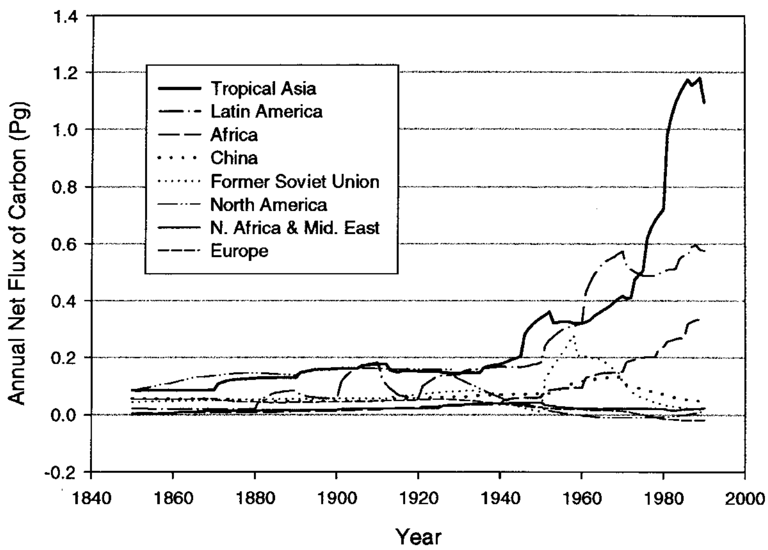

Fig. 5. Net annual flux of carbon to the atmosphere from changes in land use in different regions of the world.

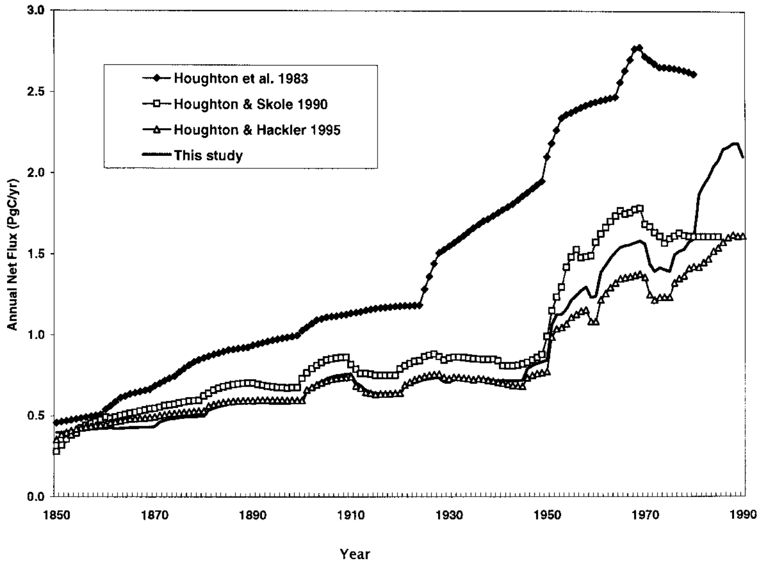

Fig. 6. Estimates of the annual net flux of carbon to the atmosphere from land-use change.

Table 3. *Estimates of the global flux of carbon to the atmosphere from changes in land use*

	1850–1980 Total flux (PgC)	1850–1990 Total flux (PgC)	1980 Total flux ($PgC\ yr^{-1}$)	1980–1990 Average ($PgC\ yr^{-1}$)
Estimate				
Houghton et al. (1983)	180*	NA	2.6	NA
Houghton and Skole (1990)	110	NA	1.6	NA
Houghton (1993)	106	122	1.4	1.6
Houghton and Hackler (1995)	98	115	1.4	1.6
this study	109	124	1.6	2.0

* 1860–1980.

amount of soil carbon lost with cultivation was assumed to be 50%. Observations of a 50% reduction generally apply to the upper 20–30 cm of the soil column, but the values of soil carbon used in the analysis referred to carbon stored in the top 1 m of soil. Thus in subsequent analyses the loss of soil carbon with cultivation was revised to 25–30% (Davidson and Ackerman, 1993). Second, estimates of forest biomass in Latin America and Africa were high in the original analysis and were subsequently lowered to accommodate updated estimates (Brown et al., 1989). And finally, harvest of fuelwood was initially included with the harvest of industrial wood. Because the two types of harvest involve very different efficiencies of wood removal, fuelwood and industrial wood harvests were subsequently simulated independently.

The global estimate presented here for the 130-year period 1850 to 1980 (109 PgC) is almost identical with the estimate of Houghton and Skole (1990) (110 PgC) despite numerous revisions to the analysis over the last 8 years. The revisions decreased the estimated flux from Latin American and increased it in tropical Asia.

The estimate presented here is higher than the estimate previously available from the Carbon Dioxide Information and Analysis Center (CDIAC) (Houghton and Hackler, 1995), and higher than the estimate used in model calculations for the 1995 update of the IPCC scientific assessment (Schimel et al., 1996) (see also Houghton, 1993; Wigley and Schimel, in press). The higher estimate resulted from several revisions both upwards and downwards. The estimate of flux presented here was reduced because the response of soil carbon to cultivation was over-estimated in some of the temperate zone countries, and because changes in programming have yielded a more direct (and accurate) method for linking historical data on wood harvests to input data required by the model.

Overall, however, the revisions increased the estimated flux, largely from tropical Asia. In the earlier analysis of tropical Asia (Houghton and Hackler, 1994), the flux of carbon from harvest of wood was calculated with a degradation ratio from Flint and Richards (1994). Flint and Richards determined that for every TgC emitted to the atmosphere from deforestation in Asia, another 0.5 TgC was lost from forests disturbed but not cleared. The ratio (50% in this example) varied over time and represented the loss of carbon from selective logging, shifting cultivation, fire, and grazing within forests. Numerous studies throughout the tropics support the observation that the biomass of tropical forests has decreased in recent years as a result of human activity (Uhl and Vieira, 1989; Woods, 1989; Gajaseni and Jordan, 1990; Brown et al., 1991, 1994; FAO, 1993; Brown and Gaston, 1995). In our previous analysis, the degradation ratio from Flint and Richards (allowed to vary through time) was used to convert forests of high biomass to forests of low biomass. Some of the carbon lost in the transition was emitted to the atmosphere, and some was added to decay pools and wood products. Because harvest and recovery were not explicitly modeled, the analysis did not include the uptake of carbon in forests recovering from harvests. Only the net change was included, not the dynamics of loss and re-accumulation.

In contrast to the earlier analysis based on a degradation ratio, the revised analysis, included here, simulated wood harvest explicitly, using annual rates of industrial and fuelwood production (in m^3) to calculate the area of forest harvested and subsequently regrowing. This revision changed the total long-term flux little, although it reduced the annual net flux in the early years of the period and increased it in the more recent years. Other revisions included a reduction in the residence time of plant debris removed from sites cleared for croplands, a consideration of plantations, and an updating of deforestation rates (FAO, 1997). The most significant consequence of these revisions was to increase the estimated release of carbon in the last decade from 1.6 PgC yr^{-1} (Houghton and Hackler, 1995) to 2.0 PgC yr^{-1}, almost all of it from the tropics (Fig. 6). Thus the discrepancy between a tropical source of carbon from land-use change (described here) and the tropical balance of carbon found in some analyses of the global carbon budget (Keeling et al., 1996; Rayner et al., 1999) appears to be somewhat larger than previously estimated.

Despite the higher estimate of the long-term estimate given here for south and southeast Asia, it is about 30% lower (over the period 1860–1980) than one determined independently by Flint and Richards (1994). The major difference is the amount of carbon estimated to have been lost from forests through selective logging. Based on the difference between their analysis and the one presented here, the overall uncertainty of the calculated flux is estimated to be within $\pm 30\%$. Conservatively, the errors associated with the estimates of flux for the 1980s are thought to be less than $\pm 50\%$ (Table 2).

Outside the tropics, recent analyses based on data from forest inventories suggest that the observed rate of carbon accumulation in forests is 0.6–0.8 PgC yr^{-1} greater than estimated here (Dixon et al., 1994; Houghton, 1996, 1998). The difference may be the result of environmental factors unrelated to changes in land use, or it may be from practices of forest management not adequately modeled in this analysis, practices such as silviculture or fire suppression. Large areas of forest in Canada and Russia, unaffected by land-use change, were ignored in this analysis. These forests may, nevertheless, be accumulating carbon as a result of variations in natural disturbance (Kurz et al., 1995) or as a result of environmental change.

4.2. *Implications for the global carbon balance*

For the 1980s the most recent IPCC interpretation of the global carbon balance is as follows (Schimel et al., 1996):

$$\underset{\text{increase}}{\text{atmospheric}} = \underset{\text{fuel}}{\text{fossil}} + \underset{\text{from changes in tropical land use}}{\text{net emissions}} - \underset{\text{uptake}}{\text{oceanic}} - \underset{\text{northern forest regrowth}}{\text{uptake by}} - \underset{\text{terrestrial sink}}{\text{residual}}$$

$$3.3(\pm 0.2) = 5.5(\pm 0.5) + 1.6(\pm 1.0) - 2.0(\pm 0.8) - 0.5(\pm 0.5) - 1.3(\pm 1.5) \quad (1)$$

The "residual terrestrial sink" is attributed to a combination of effects: CO_2 fertilization, nitrogen deposition, and inter-annual variability in climate, all of which could be causing enhanced terrestrial carbon storage anywhere on the earth. However, the distribution of terrestrial fluxes in eq. (1) among a tropical source from changes in land use, an uptake by northern forest regrowth, and a residual flux is somewhat misleading. The estimate of 1.6 ± 1.0 Pg cited for "net emissions from changes in tropical land use" is from an analysis of land-use changes at all latitudes (Houghton and Hackler, 1995); it includes 1.5 ± 0.5 Pg for tropical forests and 0.1 ± 0.5 for temperate forests (Table 2). Analyses of land-use change in northern forests suggest that the net uptake by forest growth is approximately balanced by releases of carbon from decay of logging debris and forest products. The error terms for this balance of 0.0 ± 0.5 Pg for temperate forests overlaps with the 0.5 ± 0.5 estimate cited by Schimel et al. (1996), but Schimel et al. based their estimate on the results of recent forest inventories that may include the effects of factors other than simply regrowth of northern forests following land-use change. The results of forest inventories (Kauppi et al., 1992; Birdsey et al., 1993; Kolchugina and Vinson, 1993; Apps and Kurz, 1994; Shvidenko and Nilsson, 1997, 1998; Turner et al., 1995) show that the uptake of carbon in forest growth is greater than expected for forests recovering from earlier logging (Houghton, 1996, 1998). The greater observed uptake may be the result of errors; it may indicate that forests are recovering from past natural disturbances in addition to logging; or it may be that forest productivity has been stimulated by CO_2 fertilization, increased N mineralization, and/or N deposition. Such an excess in uptake should indeed appear in eq. (1), but it cannot be attributed only to "forest regrowth" as distinct from CO_2 fertilization, nitrogen fertilization, or climatic effects (i.e., "residual terrestrial uptake").

A more nearly precise equation for the global carbon balance, and one that includes the results reported here, is the following:

$$\underset{\text{increase}}{\text{atmospheric}} = \underset{\text{fuel}}{\text{fossil}} + \underset{\text{from changes in land use}}{\text{net emissions}} - \underset{\text{uptake}}{\text{oceanic}} - \underset{\text{terrestrial sink}}{\text{residual}}$$

$$3.3(\pm 0.2) = 5.5(\pm 0.5) + 2.0(\pm 0.8) - 2.0(\pm 0.8) - 2.2(\pm 1.3) \quad (2)$$

In addition, about a quarter of the residual terrestrial uptake, or 0.6 ± 0.5 PgC yr^{-1}, has been observed in northern forests (Houghton, 1998).

Although the residual sink term in eq. (2) is believed to be a terrestrial one, the mechanisms responsible for the terrestrial accumulation of carbon are unclear. Several of the potential mechanisms are expected to become less effective in the future, leading to a diminished sink and, perhaps, an additional terrestrial source (Houghton et al., 1998; Walker et al., 1998).

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