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TROPICAL DEFORESTATION AND THE GLOBAL CARBON BUDGET

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ABSTRACT

The CO_2 concentration of the atmosphere has increased by almost 30% since 1800. This increase is due largely to two factors: the combustion of fossil fuel and deforestation to create croplands and pastures. Deforestation results in a net flux of carbon to the atmosphere because forests contain 20–50 times more carbon per unit area than agricultural lands. In recent decades, the tropics have been the primary region of deforestation. The annual rate of CO_2 released due to tropical deforestation during the early 1990s has been estimated at between 1.2 and 2.3 gigatons C. The range represents uncertainties about both the rates of deforestation and the amounts of carbon stored in different types of tropical forests at the time of cutting. An evaluation of the role of tropical regions in the global carbon budget must include both the carbon flux to the atmosphere due to deforestation and carbon accumulation, if any, in intact forests. In the early 1990s, the release of CO_2 from tropical deforestation appears to have been mostly offset by CO_2 uptake occurring elsewhere in the tropics, according to an analysis of recent trends in the atmospheric concentrations of O_2 and N_2. Interannual

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variations in climate and/or CO_2 fertilization may have been responsible for the CO_2 uptake in intact forests. These mechanisms are consistent with site-specific measurements of net carbon fluxes between tropical forests and the atmosphere, and with regional and global simulations using process-based biogeochemistry models.

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INTRODUCTION

The CO_2 concentration of the atmosphere has increased from $\sim$ 280 parts per million volume (ppmv) in 1800 to $\sim$360 ppmv in 1995. This increase is due largely to two factors: the combustion of fossil fuel and deforestation to create croplands and pastures. Deforestation results in a net flux of carbon to the atmosphere because forests contain 20–50 times more carbon per unit area than agricultural lands. The importance of deforestation relative to fossil-fuel combustion for the atmospheric CO_2 increase has changed over the past 200 years. Prior to 1900, the emissions of carbon resulting from deforestation were greater than those from fossil-fuel burning (1, 2, 3). Today, fossil-fuel use releases several times as much CO_2 into the atmosphere as deforestation (3). The regions undergoing deforestation have also changed over time. In the eighteenth and nineteenth centuries, the expansion of croplands in Europe, Russia, and North America was the major cause of deforestation. Early in the twentieth century, however, deforestation in these areas slowed; later in the century, particularly after the end of World War II, deforestation in the tropical areas of Latin America, Africa, and Asia accelerated (4). By 1980, almost the entire flux of CO_2 to the atmosphere resulting from deforestation was from the tropics (5); the release of carbon from deforestation in temperate and boreal regions was extremely small at that time (6). The purpose of this paper is to review recent analyses of the consequences of deforestation for the global carbon budget, with an emphasis on deforestation during the past several decades.

DATA REQUIRED FOR CALCULATING CARBON FLUX TO THE ATMOSPHERE FROM DEFORESTATION

The emissions of carbon from deforestation are calculated from several types of data, including rates of deforestation, stocks of carbon in vegetation and in soil per unit area of forest and of cleared land, and the fate of the deforested land.

Global and Regional Rates of Deforestation

Most of the recent estimates of carbon flux resulting from deforestation in the tropics worldwide have relied heavily on one or more of the following surveys of deforestation rates: Myers (7, 8); Food and Agricultural Organization (FAO)/United Nations Environment Program (UNEP) (9); FAO (10); World Resources Institute (WRI) (11). The first two surveys of pan-tropical deforestation were those of Myers (7) and FAO/UNEP (9). They reported deforestation rates for the late 1970s, and both considered closed forests. In the FAO/UNEP survey, closed forests were defined as dense forests that do not allow sufficient penetration of light for grasses to grow on the forest floor. The Myers estimate of deforestation for closed forests for the entire tropics was 7.6×10^6 hectares (ha) year^{-1}, a rate only slightly higher than the 7.3×10^6 ha year^{-1} reported by FAO/UNEP (Table 1). At the regional level, the estimates were the same for Africa, but Myers' estimate was 10% lower than FAO/UNEP's for Latin America and about 45% higher for Asia (Table 1).

The FAO/UNEP survey also considered open forests, whereas the Myers survey did not. Open forests, also called woodlands and savannas, have grasses present between trees or clumps of trees. According to the FAO/UNEP study, deforestation of open tropical forests was about 4.0×10^6 ha year^{-1} in the late 1970s. The FAO/UNEP estimate for the total annual rate of tropical deforestation, open plus closed, for the late 1970s was thus 11.3×10^6 ha (Table 1).

For the decade since the late 1970s, estimates of the rate of deforestation in the tropics have increased substantially (Table 1). Myers (8) reported that the annual loss of closed forests had almost doubled, from 7.6×10^6 ha year^{-1} in 1979 to 13.9×10^6 ha year^{-1} in 1989. WRI (11) has also published global estimates for deforestation rates for closed tropical forests during the late 1980s. The WRI estimate, at 16.5×10^6 ha year^{-1}, was higher than Myers' estimate. Considering both closed and open forests, FAO (10) recently reported a worldwide tropical deforestation rate of 15.4×10^6 ha year^{-1}. According to FAO,

Table 1 Estimates of rates of tropical deforestation and relative increases (percent) over the decade of the 1980s[a,b]

	Latin America	Africa	Asia	All tropics	References
FAO/UNEP					
Late 1970s[c]	4.1	1.3	1.8	7.3	9
FAO					
1976–1980[d]	5.6	3.6	2.0	11.3	10
1981–1990[d]	7.4	4.1	3.9	15.4	
Percent increase	32	12	93	36	
Myers					
1979[e]	3.7	1.3	2.6	7.6	7, 8
1989[e]	7.7	1.6	4.6	13.9	
Percent increase	108	23	77	83	
Myers modified[f]					
1989	4.5			10.7	8
Percent increase	22			41	

[a]Estimates given in values of 10^6 ha year^{-1}.
[b]Modified from (12).
[c]Closed forests only.
[d]From FAO/UNEP (9), FAO (10); closed and open forests.
[e]Myers (7,8); closed forests only.
[f]Revised rates and percent increases for Latin America are based on an average annual rate of deforestation for the 1980s in Brazil of 1.8×10^6 rather than 5.0×10^6 ha year^{-1}.

this represented a 36% increase in the average annual deforestation rate for the period 1981–1990, relative to the period 1976–1980. The FAO calculation of the percentage increase included upward revisions of the FAO/UNEP (9) estimates of deforestation rates for the late 1970s, especially for some of the larger Asian countries (Table 1).

Rate of Deforestation in Brazil

Based on information from the early 1970s, FAO/UNEP (9) estimated that 10 countries contained more than 75% of the world's tropical forests; one of those, Brazil, contained about 31% of the total (Table 2). Most of Brazil's tropical forests are located within an area known as the Legal Amazon, which includes all of the states of Acre, Amapa, Amazonas, Para, Rondonia, and Roraima, plus parts of Mato Grosso, Maranhao, and Tocantins. This area encompasses about 500×10^6 ha, of which about 400×10^6 ha is forest, 90×10^6 ha is cerrado (open woodland), and 10×10^6 ha is water.

Over the past two decades, Brazil has had the highest rates of tropical deforestation in the world, although the estimates of these rates span a wide range for the period of the 1980s. At the upper end of the range are the estimates of WRI (11) and Myers (8) (Table 2). The WRI estimate was based on a study by Setzer & Pereira (13), who used advanced, very high resolution radiometry (AVHRR) data from the NOAA-7 satellite to determine the number of fires in the Legal Amazon during the dry season period of mid-July through September, 1987. From the number of fires, they produced their estimate of the area of forest cleared. Their estimate of the deforestation rate in 1987 was 8.0×10^6 ha year^{-1}, and it was included without change in the WRI study. Myers (8) also based his estimate of deforestation in Brazil in the late 1980s on the work of Setzer & Pereira (13), but he reduced their estimate to avoid multiple accounting of single fires that burned for more than one day. Myers estimated the Brazilian deforestation rate for the late 1980s to be 5.0×10^6 ha year^{-1}.

In light of more recent studies, however, the estimates of deforestation made by WRI and Myers seem much too high. The recent studies use data from satellites, such as Landsat, that are more spatially resolved (finer scale) than the NOAA-7 data. Brazilian scientists at the Instituto Nacional de Pesquisas Espaciais (INPE) have estimated that the average rate of deforestation of closed forests in the Legal Amazon over the period 1978 through 1989 was 2.1×10^6 ha year^{-1} (14). Detailed documentation of the evolution of the official Brazilian deforestation estimate can be found in a series of papers published between 1980 and 1992 (15–18). Skole & Tucker (19), two scientists from the United States, have reported an even lower average rate of 1.5×10^6 ha year^{-1} from 1978 to 1988. And Fearnside (14) estimated that by 1991, the annual rate of deforestation in the Brazilian Amazon may have been as low as 1.1×10^6

Table 2 Estimates of forest areas and deforestation rates for the 10 countries with the largest tropical forest areas as of the early 1970s. Deforestation-rate estimates are for the late 1970s and late 1980s

	Forest area		Deforestation rates		
Country	Total forest area (10^6 ha)	Percent of world total	FAO/UNEP (9) (late 1970s) (10^6 ha year^{-1})	Myers (8) (late 1980s) (10^6 ha year^{-1})	WRI(11) (late 1980s) (10^6 ha year^{-1})
Brazil	356	30.7	1.36	5.00	8.00
Indonesia	113	9.8	0.55	1.20	0.90
Zaire	106	9.1	0.17	0.40	0.18
Peru	69	6.0	0.24	0.35	0.27
Columbia	46	4.0	0.80	0.65	0.82
India	46	4.0	0.13	0.40	1.50
Bolivia	44	3.8	0.06	0.15	0.09
Papua, New Guinea	34	2.9	0.02	0.35	0.02
Venezuela	32	2.7	0.12	0.15	0.12
Burma	31	2.7	0.09	0.80	0.68
Total	877	75.7	3.54	9.45	12.58

Table 3 Estimates of vegetation carbon stocks in closed tropical forests using two different methods[a]

	Latin America	Africa	Asia
Direct biomass measurments[b]	165	185	200
Biomass estimates from volume			
Estimates from early 1980s[b]	85	95	110
Estimates from late 1980s			
Undisturbed	90	135	110
Partially logged	75	110	60

[a] Units are metric tons (Mt) C/ha. Values rounded to the nearest 5 Mt.
[b] Average of evergreen and seasonal forest vegetation C.

ha year^{-1}. If these recently reported deforestation data for Brazil are better estimates than the one used by Myers, the pan-tropical deforestation rate may have increased during the decade of the 1980s by about 41% rather than by Myers' original estimate of just over 83% (Table 1).

Carbon per Unit Area

Forests hold more carbon per unit area in vegetation and soils than the ecosystems that replace them. Carbon is released to the atmosphere through burning at the time of deforestation and through decay of plant material and soil organic matter in the years following. The amount of carbon released per unit area depends on the amount of carbon held in forests and in the ecosystems that replace them; cleared lands may hold 20–50 times less carbon per unit area than forests.

VEGETATION Estimates of the amount of carbon held in the vegetation of the closed tropical forests of Latin America, Africa, and Asia differ by a factor of almost two (Table 3). The high estimates are based on direct, destructive sampling that involves cutting and weighing trees and other vegetation to determine plant carbon stocks. The low estimates are based on the volumes of growing stocks of wood that are then converted to stocks of carbon (20–22). A comparison of the estimates of carbon stocks (Table 3) shows that those based on direct measurements (23–25) are generally similar to each other but are about twice the value of those derived from wood volumes (20). Recent work by Brown et al (26) has revised the lower estimates upwards slightly for undisturbed closed forests (Table 3), but large differences remain between the estimates from the two approaches. In addition, Brown et al (26) note (Table 3) that many areas that are being deforested today have already been partially logged, so the carbon stocks at the time of deforestation might even be lower than those estimated earlier by Brown & Lugo (20).

At least two factors have been identified that singly or in combination may contribute to the differences between estimates from the two approaches (27). The first is the representativeness of the two estimates. The direct biomass estimates have been based on vegetation sampled in fewer than 30 ha worldwide (26), whereas the volume-derived estimates of biomass have been based on surveys of thousands of ha of closed tropical forest. Thus, the volume-based estimates may be more representative, but they are not without problems. Second, errors may still be present in the factors used to convert volumes of merchantable wood to total carbon stocks.

Which set of estimates is more accurate is not clear (20, 27–29). Because of this, a number of studies that estimate carbon losses from land due to tropical deforestation have used both sets of estimates in a sensitivity-analysis mode.

SOILS Several estimates have been made of the amount of organic carbon in the top meter of soil in tropical forests. The estimates have been stratified in various ways, including stratification into major soil classes (30), vegetation types (31, 32), and life zones (24, 32, 33), which are defined as potential vegetation zones determined by climatic variables.

About one third of the total mass of organic carbon stored in the world's soils to a depth of 1 m is found in the tropics (30). Eswaran et al (30) estimated that of the 506 gigatons carbon (Gt C or 10^{15} g C) found in tropical soils, 206 is in soils of closed tropical forests. Four major soil orders—histosols, oxisols, ultisols, and andisols—account for more than 95% of the 206 Gt C (Table 4). Histosols are wet, organic soils, and they are particularly prominent in the Sumatra, Kalimantan, and peninsular Malaysia regions of the humid tropics of Asia. These organic soils are difficult to manage for agriculture because they subside upon drainage and cultivation, and they are deficient in micronutrients such as copper. Oxisols and ultisols are often referred to as acid infertile soils. Although they are generally well drained, they have a variety of chemical limitations: high soil acidity; aluminum toxicity; and deficiency of one or more of the following nutrients: phosphorus, potassium, calcium, magnesium, sulfur, and zinc (and other micronutrients). With proper management, including fertilization, these soils can often be productive for agriculture. Andisols form from volcanic glass and nearly always have a high organic content. These soils support some of the most productive, stable, and sustainable agricultural systems in the tropics, such as those on the Indonesian island of Java.

Changes in Carbon with Disturbance

The use of deforested lands is another factor that affects the net flux of carbon to the atmosphere. Analyses of the effects of deforestation on terrestrial carbon balance usually consider the conversion of forests and woodlands to various forms of agriculture, including permanent croplands, shifting cultivation plots, and pastures. In addition, some of the analyses also consider the abandonment of croplands and pastures, the harvest of timber, and the establishment of tree plantations.

As forests and woodlands are cleared for croplands, shifting-cultivation plots, or pastures, some of the wood may be harvested for products that oxidize at varying rates. Most of the above-ground biomass is burned and released immediately to the atmosphere as CO_2. The remainder of the above-ground and below-ground material decays. The rates of decay vary with climate and the chemical composition of the plant material (34–36), but in the moist tropics most material decomposes within 10 years. A small fraction of the plant material burned is converted to black carbon, which is resistant to decay (29, 37–41). When croplands and pastures are abandoned, these areas may return to forests at rates determined by the intensity of disturbance and climatic factors (24, 42). When severely degraded agricultural land is abandoned it may become shrubland rather than forest.

Cultivation of forest soils generally results in a loss of organic carbon (43, 44). Estimates vary, but on average about 25% of the carbon in the surface horizons seems to be lost to the atmosphere when forest soils are cleared of vegetation and cultivated. The loss is exponential, with most of the loss occurring within the first 5 years following clearing.

Table 4 Organic C in tropical forest soils—those soils that are under closed forest or can support a closed forest[a]

Order	Organic C		
	Tropical soils (Gt)	Tropical forest soils (Gt)	Forest soils (% of total)
Histosols	100	100	100
Oxisols	119	43	36
Ultisols	85	30	35
Andisols	47	25	53
Alfisols	30	4	13
Inceptisols	60	2	3
Entisols	19	1	5
Vertisols	11	1	9
Aridisols	29	0	0
Spodosols	2	0	0
Miscellaneous land	2	0	0
Total	506	206	41

[a] Modified from (30).

The effect on soil carbon stocks of the conversion of forests to pastures is highly variable. Some studies show a loss of carbon (29, 43, 45–53). On the other hand, under some conditions there appears to be no loss of soil carbon (54, 55), and there may even be an increase (49, 53, 56–60). Buschbacher et al (61) have suggested that these differences in pasture soil carbon are largely related to the time since clearing and the intensity of use.

Shifting cultivation is common in the tropics. It involves short periods of cropping and long fallow periods, during which forests regrow. Because of the partial recovery of forests during the fallow period, deforestation for shifting cultivation releases less carbon to the atmosphere than deforestation for permanent croplands or pastures. The length of the fallow period varies considerably among regions, owing to both ecological and cultural differences (62, 63). The decay rates of plant debris resulting from the cutting, as well as the accumulation rates for regrowing vegetation during the fallow periods, have been determined for a variety of ecosystems, especially in Latin America (24, 64–66). Shifting cultivation results in less soil carbon loss through oxidation than does continuous cultivation (43, 44).

CALCULATING CARBON FLUX TO THE ATMOSPHERE FROM DEFORESTATION

Several accounting-type models, all with similar structures, have been used to calculate the annual net flux of carbon between the land and atmosphere that result from deforestation (67–69). The first of these to be developed, the Marine Biological Laboratory/Terrestrial Carbon Model (MBL/TCM), has been used since the early 1980s (see e.g. 2, 4–6, 67, 70, 71). The MBL/TCM considers the changes in terrestrial carbon stocks associated with clearing of forests for agriculture, and the changes associated with subsequent abandonment of the agricultural plots and the regrowth of forests (Figure 1). In the year of deforestation, a large amount of carbon is released through burning. Afterwards, decay of soil organic matter, logging debris (slash), and wood products release carbon to the atmosphere. If the agricultural plots are abandoned, regrowth of live vegetation and redevelopment of soil organic matter withdraw carbon from the atmosphere and accumulate it on land. In the MBL/TCM, these changes have been defined for various types of land use and ecosystems in various regions of the tropics and other regions. Annual changes in the various reservoirs of carbon (live vegetation, soils, slash, and wood products) determine the annual net flux of carbon between the land and atmosphere. Because of the variety of ecosystems and land uses, and because the calculations require accounting for

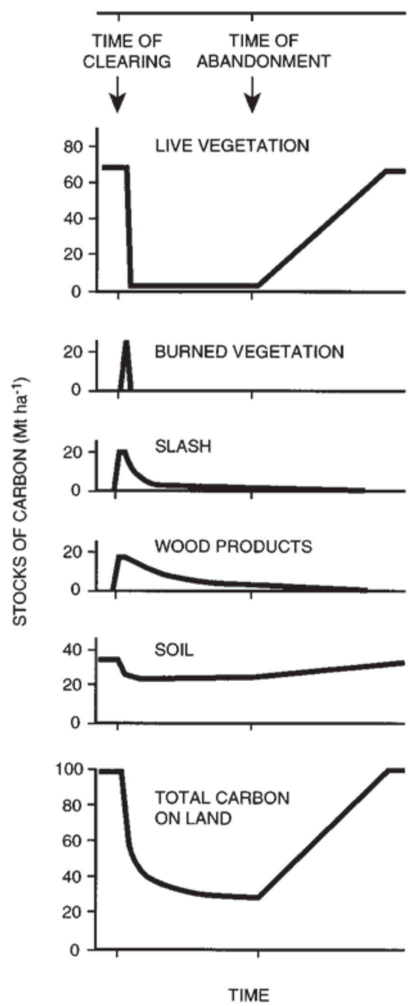

Figure 1 Changes in the reservoirs of carbon in a tropical moist forest that was cleared for croplands, cultivated, and then abandoned. The abandoned land is assumed to return to moist forest of the same stature as the original forest. Based on response functions of MBL/TCM (see e.g. 2, 4–6, 67, 70, 71). Note: slash = logging debris.

different cohorts, the MBL/TCM and the other accounting models have some level of geographic specificity and usually operate on an annual time step.

ESTIMATES OF CO_2 RELEASED FROM TROPICAL DEFORESTATION

For 1980

Using a slightly modified version of the MBL/TCM, Houghton et al (70) estimated that in 1980, tropical deforestation resulted in a net flux of carbon from the land to the atmosphere of between 0.9 and 2.5 Gt C. This range is higher than the one reported by Molofsky et al (68); 0.6–1.1 Gt C. They based their study on a model very much like the MBL/TCM, and they used the same FAO/UNEP study as did Houghton et al (70) to provide estimates of deforestation and forest biomass. Molofsky et al (68) did not include the deforestation of fallow areas. Houghton et al (70) reported that deforestation of fallow areas released between 0.4 and 0.8 Gt C to the atmosphere. If deforestation of fallow lands was ignored by Houghton et al (70) in their analysis, the ranges of Molofsky et al (68) and Houghton et al (70) would be very similar.

In 1987, the carbon fluxes associated with tropical deforestation reported by Houghton et al (70) were disaggregated among 76 tropical countries on the basis of country-specific data given by FAO/UNEP (9). In this analysis, Houghton et al (5) estimated that five countries—Brazil, Indonesia, Colombia, Ivory Coast, and Thailand—contributed about half of the total net release in 1980 (Table 5).

Since 1987, at least five additional estimates have been published of the loss of carbon from the tropics due to deforestation in 1980 (22, 27, 71–73). These recent estimates of the net release of carbon from tropical deforestation (Table 6) have generally been lower than the mid-range given by Houghton et al (5). Detwiler & Hall (72), using a model similar to the MBL/TCM, and the same sources of data for rates of deforestation and for carbon stocks, calculated a range of $0.4–1.6 \times 10^{15}$ g C. Why this estimate was different from the estimate of Houghton et al (5) is not clear.

Recently, both Hall and Houghton have revised their earlier estimates downward for 1980 (Table 6). Hall & Uhlig (22) used the new vegetation biomass numbers suggested by Brown et al (26) and new data on deforestation rates for the open forests of Latin America (74). The range estimated by Hall & Uhlig for 1980 was 0.5–1.0 Gt C, with a best estimate of 0.6 Gt C. Houghton has produced two revised estimates for 1980. The first, published in 1991, reported the results of a factorial experiment that used forest biomass numbers suggested by Brown et al (26) with several estimates of deforestation rates, including those given by Myers (7) and the Myers' estimates $\pm 25\%$. The full range of the

Table 5 Net release of carbon to the atmosphere (10^{12} g/year^{-1} or Tg) in 1980, from deforestation in the tropics[a]

	Closed forest	Open forest	Fallow	Total
Latin America				
Brazil	207	40	89	336
Columbia	85	1	40	126
Peru	31	0	14	45
Ecuador	28	0	12	40
Mexico	33	0	0	33
Other	65	5	15	85
Subtotal	449	46	170	665
Africa				
Ivory Coast	47	12	42	101
Nigeria	30	4	26	60
Zaire	27	8	0	35
Sudan	0	26	0	26
Madagascar	12	0	11	23
Other	42	75	11	128
Subtotal	158	125	90	373
Asia				
Indonesia	70	2	120	192
Thailand	33	5	56	94
Laos	30	3	51	84
Philippines	21	0	36	57
Myramar	19	0	32	51
Other	97	1	45	143
Subtotal	270	11	340	621
All Tropics Total	877	182	600	1659

[a] Modified from Houghton et al (5).

factorial experiments was 0.6–2.5 Gt C, and the likely range was 1.0–2.0 Gt C (75). Houghton's second set of revised estimates was produced in 1995 (71). For these, he used lower rates of deforestation for Latin America, higher rates of deforestation for Asia, and the forest biomass estimates of Brown et al (26). The result of these changes was an estimate of 1.3 Gt C ± 30% in 1980.

Hao et al (73) used an approach that differed from the others. They considered only the releases associated with burning. The Hao et al (73) estimate for 1980 was a range of 0.9–2.5 Gt C, which is identical to an early estimate of Houghton et al (70).

For 1989, 1990

Using a slightly modified version of the MBL/TCM, Houghton has recently published one estimate of net carbon flux from land to the atmosphere resulting from tropical deforestation for 1989 (27) and another for 1990 (71). The estimate for 1989 was based on Myers' 1991 estimate of tropical deforestation, which contained what we now think was a high estimate of deforestation in Latin America (see above discussion on Rate of Deforestation in Brazil). When Houghton used Myers' estimates of deforestation with a range of estimates of carbon stocks, and several different assumptions about the role of shifting cultivation in deforestation, the net flux of carbon in 1989 was estimated to be between 1.1 and 3.6 Gt C, with the likely range estimated at between 1.5 and 3.0 Gt C for that year.

Houghton's latest estimate for net carbon flux from the land to the atmosphere due to deforestation, for 1990, is 1.7 Gt C (71). For this most recent estimate, Houghton used the biomass numbers of Brown et al (26) and new estimates of deforestation rates for Latin America and Asia. The Latin America estimate was revised downward from the number used by Houghton in his 1991 paper (27) to reflect the recent reevaluation of deforestation rates in Brazil (see above discussion on Rate of Deforestation in Brazil). The Asian estimate was revised upward from the one used by Houghton in his 1991 paper (27) to be consistent with FAO's recent work for this region (10). For 1990, Houghton (71) calculated emissions from Latin America and Asia to be about 0.7 Gt C, and from Africa about 0.35 Gt C.

CARBON BALANCE IN UNDISTURBED TROPICAL FORESTS

Anthropogenic emissions of CO_2 in 1990 amount to about 5.6 Gt C from fossil-fuel burning and about 1.7 Gt C from tropical deforestation, whereas the annual increase in carbon in the atmosphere as CO_2 was only about 3.4 Gt C. The

Table 6 Recent estimates of net carbon flux from the land to the atmosphere resulting from tropical deforestation E[a]

Study	Net flux of carbon (Gt C in 1980)	Net flux of carbon (Gt C in 1989, 1990)
Molofsky et al (68)	0.6–1.1	
Houghton et al (Table 5; 5)	0.9–2.5	
Detwiler & Hall (72)	0.4–1.6	
Hao et al (73)	0.9–2.5	
Hall & Uhlig (22)	0.6[b]	
Houghton (75)	1.0–2.0	1.5–3.0
Houghton (71)	1.3	1.7[c]

[a]Estimates are for two years, 1980 and 1990, unless noted.
[b]Best estimate, range 0.5–1.0.
[c]Range 1.2–2.3.

difference of about 3.9 Gt C in 1990 is presumed to be distributed among the oceans and terrestrial ecosystems. Ocean uptake has been estimated at about 2.0 Gt C, with terrestrial ecosystems storing the remainder of the carbon, about 1.9 Gt. Are undisturbed tropical forests storing any of this carbon, and if so, what factor or set of factors is responsible for this storage?

Recent reviews of the global carbon budget suggest that three factors lead to increased carbon storage: forest regrowth following harvest; nitrogen deposition, especially downwind of the industrial and agricultural regions; and CO_2 fertilization (3, 76, 77). The first two factors are thought to be operating primarily in the mid-latitudes of the northern hemisphere, whereas CO_2 fertilization is considered to be operating globally, including in tropical forests.

Both field studies and theoretical models support the idea that CO_2 fertilization of undisturbed tropical forests can result in enhanced carbon storage in terrestrial biomass. Two gas-flux studies in undisturbed tropical forests of Brazil's Amazon Basin have shown that photosynthetic gains of carbon dioxide exceeded respiratory losses during the measurement periods. Fan et al (78) reported a net carbon uptake of about 0.06 g m^{-2} day^{-1} over a 50-day period during 1987 by an undisturbed forest near Manaus in the central Amazon.

Grace et al (79) made measurements of carbon dioxide flux over undisturbed tropical rain forest at Reserva Jaru, Rondonia, in the western Amazon Basin of Brazil, for 55 days spanning the wet and dry seasons of 1992–1993. In the dry season, the mean accumulation rate was 1.1 g C m^{-2} day^{-1}; in the wet season the rate was 0.6 g C m^{-1} day^{-1}. They then developed a model that related net carbon flux to daily changes in light, humidity, and temperature (80). They used site-specific climatological data to run the model for 1 year (July 1, 1992—June 30, 1993). Over this period, the model estimated a carbon accumulation of 102 ± 24 g C m^{-2} $year^{-1}$. If all the rain forests of the Brazilian Amazon (400×10^6 ha) were behaving in the same way as Reserva Jaru, the carbon accumulation in this region would be 0.41 Gt C $year^{-1}$.

Theoretical models also predict an accumulation of carbon in the world's tropical forests as a result of increased CO_2 concentrations. Both Polglase & Wang (81) and Taylor & Lloyd (82) predict a net absorption by all tropical forests worldwide of about 1 Gt C $year^{-1}$ at contemporary levels of atmospheric CO_2 concentration. Melillo et al (77), using the Terrestrial Ecosystem Model (TEM), have estimated that the observed increase in CO_2 concentration has lead to a net uptake of carbon in the tropics of about 0.5 Gt C $year^{-1}$ for 1990. Net carbon uptake results from an imbalance between net primary production and heterotrophic, largely microbial, respiration. Simulations using TEM suggest that soon after the atmospheric CO_2 concentration stabilizes, heterotrophic respiration comes into balance with net primary production and the CO_2-stimulated terrestrial carbon sink disappears.

ROLE OF TROPICAL FORESTS IN THE GLOBAL CARBON BUDGET

An evaluation of the role of tropical regions in the global carbon budget must include both the carbon flux to the atmosphere due to deforestation and carbon accumulation in the undisturbed forests due to CO_2 fertilization.

The estimated range for carbon loss to the atmosphere due to deforestation in 1990 is 1.2–2.3 Gt C (71), and the estimated range for carbon gain on land due to CO_2-stimulated carbon accumulation for 1990 is 0.5–1.0 Gt C (77, 81, 82). When these estimates are combined, the tropical regions of the globe are estimated to be functioning as a net source of carbon to the atmosphere of between 0.2 and 1.8 Gt C.

This range must be regarded as very tentative. The net flux of carbon between the land and the atmosphere in the tropics could be influenced by interannual variations in climate (77, 79, 83–85) that could cause this region to function as a net carbon sink in some years and an even larger source than 1.8 Gt C in others. Keeling et al (86), who measured trends in atmospheric concentrations of O_2 compared to N_2, suggest that, for the period 1990–1994, the tropical biota as a whole were not a strong source or sink of CO_2. They argued that releases of CO_2 from tropical deforestation must have been offset by CO_2 uptake occurring elsewhere in the tropics.

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