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Tropical Forests and the Global Carbon Cycle

R. P. Detwiler and Charles A. S. Hall

New data on the three major determinants of the carbon release from tropical forest clearing are used in a computer model that simulates land use change and its effects on the carbon content of vegetation and soil in order to calculate the net flux of carbon dioxide between tropical ecosystems and the atmosphere. The model also permits testing the sensitivity of the calculated flux to uncertainties in these data. The tropics were a net source of at least 0.4×10^{15} grams but not more than 1.6×10^{15} grams of carbon in 1980, considerably less than previous estimates. Decreases in soil organic matter were responsible for 0.1×10^{15} to 0.3×10^{15} grams of the release, while the burning and decay of cleared vegetation accounted for 0.3×10^{15} to 1.3×10^{15} grams. These estimates are lower than many previous ones because lower biomass estimates and slightly lower land clearing rates were used and because ecosystem recovery processes were included. These new estimates of the biotic release allow for the possibility of a balanced global budget given the large remaining uncertainties in the marine, terrestrial, and fossil fuel components of the carbon cycle.

The concentration of carbon dioxide in the atmosphere has increased from about 280 parts per million (ppm) circa 1750 to about 345 ppm in 1984 (*1*). Because CO_2 and other trace gases (for example, methane, nitrous oxides, and chlorofluorocarbons) produced by industrial and agricultural processes absorb thermal radiation emitted by the earth's surface (*2*), researchers have predicted that the increasing concentrations of these gases in the atmosphere will result in significant changes in climate (*3*), which in turn may produce substantial changes in the location of agricultural zones and shorelines (*4*). Because the effects of CO_2 on climate are in some dispute (*5*), determining how carbon cycles among the atmosphere, hydrosphere, and biosphere is of continuing interest.

Since 1977 this interest in the global cycling of carbon has involved a controversy between terrestrial ecologists and geochemists. All participants agree that the principal cause of the increase in atmospheric CO_2 in recent years has been the combustion of fossil fuels, which released about 5.2 gigatons (GT; 1 GT = 1×10^{15} g) of carbon during 1980. The kilning of limestone for the production of cement released an additional 0.1 GT, for a total of 5.3 GT from industrial processes in 1980 (*6*). But long-term studies of atmospheric CO_2 conducted at Mauna Loa since 1958 indicate that only 55 percent of the CO_2 released from industrial activities remains in the atmosphere (*7*). The most likely repository of some or all the remaining 45 percent is the oceans. Because it is not possible at present to measure directly the increase in inorganic carbon dissolved in seawater (*8*), estimates of the ocean's uptake of CO_2 have been based on models, most of which predict relatively small oceanic uptake (*9*). Present versions of these models estimate that the oceans sequester approximately 35 percent of the CO_2 released by industry (*10*). To balance their global carbon budgets, a number of geochemists postulated that terrestrial ecosystems, like plants in greenhouses, increase their rate of photosynthesis in the presence of increasingly elevated levels of CO_2 (*11*).

In 1977, however, several terrestrial ecologists concluded that not only was it unlikely that terrestrial ecosystems would increase their carbon storage in response to increased atmospheric CO_2 but that the destruction of these ecosystems, primarily tropical forests, was releasing nearly as much CO_2 into the atmosphere as were industrial processes (*12*). In their view, the oceans were the only likely sink for both the fossil fuel CO_2 not found in the atmosphere and the CO_2 released from forest clearing (*12, 13*). Two early studies suggested that the annual releases from forest clearing could be as large as two to four times those from fossil fuels and limestone (*14*), although these estimates were later revised downward (*15*). The geochemists, however, believed that their models of oceanic CO_2 uptake were sufficiently accurate to exclude the possibility of such a large error in their estimates, and they attacked both conclusions of the ecologists. They argued that too little was known about rates of forest

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destruction and recovery to conclude that there was a significant release due to land use change, and that the possibility of CO_2 fertilization of undisturbed terrestrial ecosystems could not be dismissed (*8*). This argument has not been resolved satisfactorily a decade later despite a large research effort (*16*).

In this article we describe research undertaken to reduce the uncertainty in estimating the release of CO_2 caused by land use change. Previous studies have found that the clearing of tropical forests is responsible for both the largest proportion of, and the largest uncertainty in, the biotic release (*13, 15*). Although the destruction of temperate forests may have released significant amounts of CO_2 in the 19th century (*17*), it now appears that the net release from all nontropical regions was at most about 0.1 GT in 1980, with a greater likelihood that it was near zero (*18*). This estimate takes into account the uptake of CO_2 by expanding forests in some temperate regions, such as the southeastern United States (*18, 19*). Therefore, our research has focused on estimating the release of CO_2 due to land use change in the tropics and on whether these new results allow us to balance the global carbon budget.

How Tropical Land Use Change Affects the Atmosphere

Tropical forests are exploited by people for a variety of purposes, including timber extraction, shifting cultivation, permanent agriculture, and pasture (*20*). These various land uses differ in their effects on vegetation and soil, and, therefore, differ in the quantity of CO_2 released when a unit area of forest is converted to each of these uses (*21*). The timing of this release also varies. The burning that follows most forest clearing in the tropics converts some of the felled vegetation immediately into CO_2 (*22*). The decay of the remaining vegetation and the decline in soil organic matter adds additional CO_2 to the atmosphere for several years after an area is cleared of forest (*23*). Some of the carbon contained in the vegetation may not enter the atmosphere, but may remain sequestered indefinitely in lumber, ash, and charcoal (*24*). Much of the clearing in tropical forests is for shifting cultivation, in which areas are cultivated for 1 to 3 years and then abandoned for 8 to 20 years. During the fallow period of the cycle, trees colonize the site and grow, creating a secondary forest. This recovery of forest vegetation sequesters some proportion of the carbon released as a result of clearing; thus, it is important to distinguish between temporary and permanent clearing in the tropics because the net release of CO_2 from the former is significantly less than that from the latter (*25*).

Computer Simulations of Tropical Land Use Changes and Their Effects

We have developed a computer model in which these land use changes in the tropics are simulated and the resultant net flux of CO_2 between this region and the atmosphere calculated based on conservation of mass (*26*). The model requires three types of data: (i) the rates of land use change, including the rate at which cleared areas are abandoned; (ii) the carbon stored in the vegetation and soil of undisturbed tropical forests and the ecosystems that are replacing them, such as logged forests, secondary forests, cultivated fields, and pastures; and (iii) the fate of carbon in cleared vegetation and soils.

Rates of land use change. The scale of clearing in tropical forests varies from selective logging, in which as few as one tree per hectare is removed, to clear-cutting large tracts for permanent pasture. In many regions, forest conversion starts with selective logging and ends with degraded pastures. Forest farmers follow roads cut by loggers, practice an abbreviated form of shifting cultivation for several years, and then convey their plots to ranchers who combine these small holdings into large pastures. In other areas, much of the clearing is for traditional shifting cultivation with a fallow period sufficient to permit the growth of secondary forest (*27*). The changes in carbon storage that result from selective logging and shifting cultivation are much smaller than those that follow the conversion of forest to permanent agriculture and pasture (*23*). Thus, estimating accurately the CO_2 released by forest clearing depends on identifying the purpose for which areas of forest are cleared.

Data from the most detailed studies of tropical land use change available at present appear in Table 1. An important conclusion of these studies is that shifting cultivation, in one form or another, is by far the dominant land use in the tropics. The area cleared for shifting cultivation each year is perhaps three times as much as that cleared for other types of agriculture and pasture. These studies separate tropical forests into two broad categories: closed and open. Although there are classification systems that make finer distinctions among types of tropical forest (*28*), apportioning forest clearing according to these systems is extremely difficult, even for individual countries (*29*).

The Food and Agriculture Organization (FAO) of the United Nations estimated land use change and forest volume in more than 70 tropical countries (*30*). The total area cleared in these countries appears as the FAO estimates in Table 1. Lanly's estimates are also a summary of the FAO data (*20*). An independent estimate of forest clearing for the entire tropics was prepared by Seiler and Crutzen

Table 1. Various estimates of rates of land use change (in 10^6 hectares per year) in closed and open forests, circa 1980.

Land use change	Closed forest					Open forest			
	Seiler and Crutzen (*20*)		FAO (*30*)	Lanly (*20*)	Myers (see *32*)	Seiler and Crutzen (*20*)		FAO (*30*)	Lanly (*20*)
	Low	High				Low	High		
Primary forest to permanent use									
To pasture	1.6	1.4	1.1	2.5	0.6	1.7	2.1	0.8	1.3
To agriculture and roads	0.3	2.2	1.1	2.3	0.0	0.2	3.0	0.7	0.8
Primary forest to logged forest			4.6	3.7	4.5				
Logged forest to permanent use									
To pasture			1.1		0.6				
To agriculture			1.0		3.9				
Secondary forest to permanent use									
To pasture	0.5	1.5	0.1		3.3	1.0	1.0		
To agriculture	0.6	0.8	0.1		6.8	0.2	1.4		
Primary forest to shifting cultivation	2.6	3.6	3.2	3.4	1.9			1.2	1.7
Secondary forest to shifting cultivation	14.9	40.0	18.5	22.0	3.4	6.9	21.9	11.4	18.6

(*20*); we modified their estimates to some extent (*31*). Myers (*20, 27*) estimated rates of land use change, but for closed forests only (Table 1). The estimates presented for him are refinements of his earlier studies (*32*).

Carbon content of vegetation and soil. Brown and Lugo (*33*) have calculated two estimates of the carbon content of tropical vegetation from two distinct types of data: timber volume and destructive sampling. Using the volume data, they calculated the carbon content of primary closed forest to be 90 ton/ha and that of primary open forest to be 31 ton/ha. The destructive sampling data yielded estimates of 164 ton/ha and 40 ton/ha, respectively. According to Brown and Lugo, the estimates derived from the volume data may be more representative of tropical forests because the volume data are more numerous and because there appears to have been a bias toward selecting plots with larger vegetation in studies using destructive sampling. We used the biomass estimates derived from each type of data in separate simulations. All the estimates of the carbon content of primary forest vegetation we used are lower than those found in an earlier study often used in previous assessments of the carbon release from tropical forests (*34*).

Changes in land use affect the carbon content of soil as well as that of vegetation. Although the evidence is limited, the use of forest soils for agriculture and pasture appears to reduce their carbon content, but only within the first 40 cm of depth (*35*). The carbon content of tropical soils under forests and various land uses are given by Detwiler in (*21*). The conversion of forest soils to permanent agriculture decreases soil carbon by about 40 percent, whereas conversion to pasture reduces the carbon content by 20 percent. Selective logging appears to have little effect on soil carbon. Shifting cultivation causes an 18 to 27 percent decline in soil carbon, and approximately 35 years of forest fallow are required for the soil's carbon content to return to the level found under undisturbed forests (*35, 36*).

Fate of carbon in cleared vegetation and soil. The fate of carbon contained in cleared vegetation and soil determines the timing and size of the CO_2 release. Some of the cleared vegetation is used for lumber and other wood products, including firewood (*20*). The burning that follows most clearing in the tropics causes an immediate release of some of the carbon in cleared vegetation while converting some of the remainder into charcoal and ash (*37*), which are resistant to decay (*38*). The slash not converted by the fire into CO_2 or charcoal and ash decays over time, releasing most of its carbon to the atmosphere within 10 to 20 years (*39*). Changes in soil carbon continue for several years after clearing or abandonment.

Studies of tropical forest clearing indicate that significant amounts of the cleared vegetation become lumber, slash, charcoal, and ash as well as CO_2. The proportion of cleared vegetation converted into these materials differs in closed and open forests: the smaller stature of the vegetation and the drier climate result in the combustion of a larger proportion of felled open forest vegetation (*40*). Many studies comment on the large quantity of slash that remains after clearing and burning (*41, 42*); similarly, other studies have found significant amounts of charcoal in tropical soils (*43*). The parameters used to model the fate of cleared vegetation are minor modifications of those found in Detwiler *et al.* (*21*).

The carbon content of a forest soil that is cultivated or used for pasture can decline because of erosion, mechanical removal of topsoil by equipment, and increased oxidation of organic matter. The last is probably responsible for most of the loss (*44*), and it is the only one of these processes that affects the CO_2 content of the atmosphere directly. The size and duration of the carbon changes in tropical forest soils depends on their use after clearing. The loss caused by permanent agriculture occurs over 5 years; that caused by shifting cultivation occurs over 2 years; and that caused by pasturage apparently occurs soon after clearing. The carbon content of soils recovering from pasture or agricultural use returns to the level of soils under undisturbed forest in approximately 35 years (*35, 36*).

The simulations. The estimates of land use change for the entire tropics (Table 1) (with the exception of the FAO estimates) were combined with the estimates of carbon storage and the parameters concerning the fate of cleared vegetation to produce eight complete data sets. The model then calculated eight estimates of the carbon released by land use change in 1980. In separate analyses FAO (*30*) estimates of clearing and forest biomass in 76 tropical countries were combined with the estimates of soil carbon and other parameters to produce 76 additional data sets. We used these data sets to calculate the carbon released by forest clearing in each country, and summed these releases to produce one more estimate of the release from the entire tropics.

Results

Land use change in the tropics released no less than 0.42 and no more than 1.55 GT of carbon in 1980. The release from cleared vegetation was 0.31 to 1.30 GT during that year, while the conversion of forest soils to agricultural fields and pastures released another 0.11 to 0.25 GT (Table 2).

Clearing in Brazil, Indonesia, and Colombia was responsible for more than half the total release from all the countries examined in the FAO reports (*45*). The release from these countries and the next seven (Thailand, Ivory Coast, Zaire, Philippines, Peru, Ecuador, and Mexico) account for approximately three-quarters of the total.

Sensitivity analysis. What are the uncertainties responsible for this more than threefold difference in the estimated size of the CO_2

Table 2. Net release of carbon from tropical forests, 1980.

Data sets	Carbon release ($\times 10^9$ ton/year)
Seiler and Crutzen low estimate of land use change	
Carbon storage of vegetation based on volume data	0.42 (0.31 + 0.11)*
Carbon storage of vegetation based on destructive sampling	0.67 (0.56 + 0.11)
Seiler and Crutzen high estimate of land use change	
Carbon storage of vegetation based on volume data	0.76 (0.52 + 0.24)
Carbon storage of vegetation based on destructive sampling	1.15 (0.91 + 0.24)
FAO estimate of land use change	
Carbon storage of vegetation based on volume data	0.47 (0.31 + 0.16)
Lanly estimate of land use change	
Carbon storage of vegetation based on volume data	0.76 (0.53 + 0.23)
Carbon storage of vegetation based on destructive sampling	1.16 (0.93 + 0.23)
Myers estimate of land use change†	
Carbon storage of vegetation based on volume data	0.99 (0.74 + 0.25)
Carbon storage of vegetation based on destructive sampling	1.55 (1.30 + 0.25)

*First figure is the release from vegetation, second is the release from soils. †Myers estimated land use change in tropical closed forests only. These estimates of carbon release include the release from open forests based on Seiler and Crutzen's high estimate of land use change in these forests (Table 1). Their high estimate produced the largest release from tropical open forests.

release? How can they be reduced? The largest uncertainty resides in the varying estimates of biomass. In our simulations with biomass based on volume data, the amount of carbon released is 36 percent less than the amount from simulations in which biomass estimates are based on destructive sampling. Although the volume-based values may be more representative of the average value for all tropical forests (*46*), the vegetation on sites selected for clearing may not be representative of average tropical forest. Farmers and ranchers may select areas with more luxuriant growth for clearing in the often mistaken belief that these sites have better soils (*47*). Loggers choose sites with the largest specimens of commercially valuable species (*47*). All commercial users of tropical forests are limited to areas where roads or rivers provide access, and rivers are generally surrounded by richer soils (*48*). Thus the average biomass of forests subjected to disturbance may be different from the average for all tropical forests and the higher estimates of carbon storage may be a better representation. Clearly it would be relatively straightforward to do biomass sampling of regions while they are being cleared to improve these estimates.

The estimates of the magnitude and type of clearing are also important, for the simulations that use Seiler and Crutzen's low estimate of clearing predict releases of carbon that are 55 percent smaller than the simulations using Myers' estimate. The more recent FAO estimate of clearing rates are similar to Seiler and Crutzen's low estimates (Table 1). Even though the latter were derived from older data, they do not appear unreasonable for 1980. There is a possibility that the net release from tropical forests in 1980 could have been as low as 0.42 to 1.15 GT of carbon, the range obtained with these lower clearing rates.

The major difference between Myers' estimate of land use change and the other estimates in Table 1 is the importance of shifting cultivation. According to Myers and his colleagues (*49*), true shifting cultivation, in which fallow periods are sufficiently long to allow the growth of secondary forest, is rapidly disappearing in the tropics. He suggests that 1.9 million hectares of primary forest were converted to shifting cultivation in 1980 while 10.1 million hectares of forest fallow were converted to permanent uses (*32*). But Lanly (*50*) estimates that the area of forest fallow increased 1.1 percent in tropical America, 1.4 percent in tropical Africa, and 1.3 percent in tropical Asia in 1980. The principal reason that Myers' rates produce the largest releases of carbon is his large estimate for the amount of secondary forest permanently cleared. In a previous study, we found that determining the area under shifting cultivation in tropical countries is difficult if not impossible to determine from forestry and agricultural surveys (*51*). To resolve the controversy over the trend in the area of true shifting cultivation would require an extensive and prolonged program of remote sensing (*52*).

Comparison with other studies. All studies of the role of terrestrial ecosystems in the global carbon cycle indicate that there was a significant release of CO_2 from terrestrial ecosystems in 1980 (Table 3). Those based on land use data suggest that most of the release originated in the tropics and assume that the carbon content of mature, undisturbed ecosystems does not change from year to year. Land use studies should be compared to those based on the variation of the $^{13}C/^{12}C$ ratio in tree rings. These tracers also show the biosphere as a whole was a net source of atmospheric CO_2 in 1980, and they do include the effects of any uptake by mature ecosystems (*53*), a process often invoked by geochemists to balance the global carbon budget. Although use of $^{13}C/^{12}C$ variations in tree rings to determine the size of the CO_2 release from vegetation and soil is in theory more inclusive than use of land use data, the accuracy of this method is now judged to be questionable by some, including one of its early proponents. The uncertainty exists because variations in the isotopic composition of tree rings are caused by physiological factors as well as changes in the isotopic composition of the atmosphere (*54*). Studies of air trapped in glacial ice avoids this problem. Siegenthaler and Oeschger's (*10*) analysis of ice-core data indicate that terrestrial ecosystems released 0.0 to 1.0 GT of carbon in 1980. If CO_2 fertilization of mature ecosystems is insignificant or nonexistent, as several ecologists suggest (*55*), the inability of land use studies to detect it may be unimportant.

Table 3. Estimates of the carbon release from terrestrial ecosystems, circa 1980.

Source of estimate	World	Tropics
	Land use data	
Moore *et al.* (*70*)	2.2 to 4.7	1.8 to 3.8
Houghton *et al.* (*15*)	1.8 to 4.7	1.3 to 4.2
Houghton *et al.* (*32*)		0.9 to 2.5
Detwiler *et al.* (*21*)		1.0 to 1.5*
This study		0.4 to 1.6
	$^{13}C/^{12}C$ variations in tree rings	
Peng *et al.* (*11*)	1.2	
Emanuel *et al.* (*73*)	1.8	
Stuiver *et al.* (*74*)	0.3	
Peng (*10*)	0.5	

*More likely range; range including all simulation is 0.9 to 2.1.

Balancing the Global Carbon Budget

The estimates of the carbon released in 1980 by tropical forest clearing generated by this analysis are lower than most earlier estimates (*15, 56*). The estimates of the annual release resulting from land use change in nontropical ecosystems also have decreased: earlier studies put this release at 0.5 to 0.8 GT per year (*13, 15*) but the most recent study calculated it at 0 ± 0.1 GT per year (*18*). Although the estimates of the net release due to land use change have decreased, all recent studies still find a significant annual release for the earth as a whole. Thus the question remains as to whether the global carbon budget can be balanced.

The controversy concerning the global carbon budget centers on whether the terrestrial ecosystems are a net source or sink of atmospheric CO_2. Most models of the ocean's uptake of CO_2 require an uptake by terrestrial ecosystems to balance the total carbon budget because those ocean models cannot accommodate even the fossil-fuel CO_2 necessary to reproduce the atmospheric concentration of this gas as recorded at Mauna Loa (*57*). A net release due to forest clearing casts some doubt on these models but does not necessarily invalidate them. If both our studies and the oceanic models are accurate, some other sink must, in 1980, take up not only the fossil fuel–generated CO_2 not found in the atmosphere but also, according to this analysis, at least 0.4 GT of carbon per year released by tropical forest clearing.

Thus the potential for CO_2 fertilization of terrestrial ecosystems is an important question. Increasing the concentration of CO_2 in controlled environments increases growth in many plant species (*58*). Whether the secular rise in the CO_2 content of the atmosphere causes mature, undisturbed ecosystems to increase their carbon storage is not known (*59*). Some contend that such an increase is unlikely because growth in these ecosystems is probably limited by factors other than CO_2 (*60*), because increased growth does not necessarily lead to increases in long-term storage of carbon (*61*), or because the climatic changes that may accompany the atmospheric increase in CO_2 could accelerate the decomposition of dead organic matter (*62*). LaMarche *et al.* (*63*) attributed a recent increase in the growth of bristlecone pine that they were unable to correlate with

Table 4. Balancing the global budget, 1980.

Carbon	Flux ($\times 10^{15}$ g of carbon per year)		
	Extreme	Median	Extreme
Released			
Fossil fuel combustion; cement production (*6*)	4.8	5.3	5.8
Tropical forest clearing	0.4	1.0	1.6
Nontropical forest clearing (*18*)	−0.1	0.0	0.1
Accounted for			
Atmospheric increase (*7*)	−2.9	−2.9	−2.9
Ocean uptake (*8, 10, 66*)	−2.5	−2.2	−1.8
"Missing"*	−0.3	+1.2	+2.8

*A minus indicates the need for a source of the size shown; a plus, the need for a sink.

climatic trends to CO_2 fertilization, but others have expressed doubts about this conclusion (*64*).

The possibility that CO_2 fertilization occurs in undisturbed ecosystems cannot be dismissed; direct detection of it, however, appears expensive at present. Free air CO_2 enrichment of forest ecosystems would cost between \$1.4 and \$4.2 million per year for the CO_2 alone (*65*), and it is clear from the studies of Brown and Lugo (*33*) that our present understanding of the biomass of large tropical ecosystems is not reliable within about a factor of 2 whereas a change in their biomass of but 0.3 percent per year would sequester 1 GT of carbon per year. And, of course, the possibility of CO_2 fertilization is not limited to tropical ecosystems.

Lugo and Brown (*53*) have pointed out that the CO_2 content of the atmosphere appears to have varied widely in the period between the last glaciation and the start of the industrial revolution, indicating that there are more than anthropogenic effects at work. They also argue that mature terrestrial ecosystems have acted as a net carbon sink since 1860. The change in the carbon content of mature ecosystems necessary to balance the global carbon budget is, however, too small to detect from timber volume data or destructive sampling. Can we balance the budget without assuming an increase in the carbon storage of undisturbed ecosystems?

Our analysis estimates the size of the release from forests and soils to be 1.0 GT of carbon per year in 1980 with an uncertainty of ± 0.6 GT per year and, of course, assuming that the data we have used are accurate. There is also uncertainty as to the amount of CO_2 released from fossil fuel combustion and cement production. Marland and Rotty (*6*) estimate that these processes injected 5.3 ± 0.5 GT of carbon into the atmosphere during 1980. The box-diffusion models of oceanic uptake on which the geochemists base their conclusion that terrestrial ecosystems must have become a net sink of fossil fuel–generated CO_2 sometime during the last 50 years predict that the oceans absorbed about 1.8 GT of carbon per year in the same year (*10, 11*). This number is not normally presented with error limits, but there is some evidence that these box-diffusion models may underestimate the ability of the oceans to absorb CO_2. Takahashi (*66*) has estimated oceanic CO_2 uptake by calculating the net CO_2 flux across the air-sea interface due to differences in the CO_2 content of the atmosphere and seawater at various locations. His work suggests that the oceans may have absorbed 2.6 GT of carbon per year in 1980. In Table 4 are listed the major net fluxes in the global carbon cycle and estimates of the size of these fluxes, including the range of uncertainty in each. The lower estimates of release and the higher estimate of oceanic uptake are juxtaposed. One can see that the uncertainties in these estimates are large enough to require either another small source of atmospheric CO_2 or another large sink. Thus, there is some possibility, how large we cannot say, that the global carbon budget can be balanced without postulating another sink if the actual oceanic uptake is closer to Takahashi's estimate than to those of the other geochemists. If the other geochemists are correct, however, we must find a sink that can accommodate not only 0.1 to 1.1 GT of fossil-fuel carbon in 1980 but also 0.3 to 1.7 GT of carbon from forests.

What would markedly improve our ability to assess and perhaps balance the global carbon budget, and what would it cost? To reduce the uncertainty in the release caused by tropical forest clearing would require significantly better estimates of forest biomass, as well as rates of forest disturbance; these estimates probably cannot be obtained except by remote sensing (*52*). The FAO simulations indicate that, at least initially, any remote sensing program should focus on Brazil, Indonesia, Colombia, and the other seven countries where almost 75 percent of the release occurred in 1980. Decreasing the uncertainty surrounding tropical forest destruction also would improve our ability to predict and perhaps even reduce the threat of extinction facing many tropical species (*67*). As mentioned previously, direct detection of CO_2 fertilization in undisturbed ecosystems by experimentation would be expensive; detection by observing small changes in carbon storage of undisturbed forests seems impossible at present. Deconvolving the terrestrial release (*68*) from variations in tree-ring ^{13}C or from ice-core data yield results only as precise as the ocean models and the estimates of the fossil-fuel release one uses in these analyses. The uncertainty in the uptake predicted by these models may be ± 25 percent (*69*). To improve the accuracy requires ocean models that take into account latitudinal, longitudinal, and seasonal variations in CO_2 uptake as well as the effect of depth (*70*); such models may be a decade away. Marland and Rotty (*6*) estimate the uncertainty in the fossil fuel release for the years 1950 to 1981 to be ± 10 percent; Keeling (*71*) estimates the uncertainty for the period 1929 to 1949 to be at least ± 20 percent.

In conclusion, this study and others completed in the last decade have improved our understanding of the global carbon cycle and reduced the discrepancy in the carbon budget to a maximum of 2.8 GT of "missing" carbon in 1980; future carbon cycle research will have to address more difficult questions if it is to improve significantly upon these achievements. In the meantime, human population and economic growth, and their accompanying requirements for land, timber, and other resources, almost inevitably mean that more forests will be cleared (*72*). The net carbon released by these activities is an important component of the global carbon cycle and, as a consequence, of possible future climate changes. Concurrently, there are many other (and perhaps more important) issues associated with these land use changes, including species extinction, local climate changes, and loss of many economic resources. Given the large and important changes that are taking place it is remarkable that our quantitative estimates of tropical land use change and its consequences are so uncertain.

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