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Land use change and the global carbon cycle: the role of tropical soils

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Abstract. Millions of hectares of tropical forest are cleared annually for agriculture, pasture, shifting cultivation and timber. One result of these changes in land use is the release of CO_2 from the cleared vegetation and soils. Although there is uncertainty as to the size of this release, it appears to be a major source of atmospheric CO_2, second only to the release from the combustion of fossil fuels. This study estimates the release of CO_2 from tropical soils using a computer model that simulates land use change in the tropics and data on (1) the carbon content of forest soils before clearing; (2) the changes in the carbon content under the various types of land use; and (3) the area of forest converted to each use. It appears that the clearing and use of tropical soils affects their carbon content to a depth of about 40 cm. Soils of tropical closed forests contain approximately 6.7 $\mathrm{kg\,C \cdot m^{-2}}$; soils of tropical open forests contain approximately 5.2 $\mathrm{kg\,C \cdot m^{-2}}$ to this depth. The cultivation of tropical soils reduces their carbon content by 40% 5 yr after clearing; the use of these soils for pasture reduces it by about 20%. Logging in tropical forests appears to have little effect on soil carbon. The carbon content of soils used by shifting cultivators returns to the level found under primary forest about 35 yr after abandonment. The estimated net release of carbon from tropical soils due to land use change was $0.11–0.26 \times 10^{15}$ g in 1980.

Introduction

Organic matter is a critical factor in determining the agricultural potential of tropical soils. It influences the structure of the soil and thereby affects water infiltration and storage, aeration and root penetration. In the humid tropics, with their abundant rainfall and highly weathered soils, organic matter is a major source of nutrients and cation exchange capacity (Sanchez, 1976; Young, 1976; Lathwell and Bouldin, 1981). Given the importance of soil organic matter to tropical agriculture, it is not surprising that there is a large amount of literature on the subject. I have used this literature in an attempt to improve our understanding of the role of terrestrial biota in the global carbon cycle.

Bolin (1977) and Woodwell and Houghton (1977) first suggested that the destruction of natural ecosystems, primarily forest, and their replacement by agro-ecosystems could result in a release of carbon dioxide to the atmosphere similar in magnitude to the release from fossil fuel combustion, which

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Table 1. Estimates of the net annual release of carbon from vegetation and soil due to land use change, circa 1970–1980. All values × 10^{15} $g \cdot yr^{-1}$.

	World		Tropics	
Authority	Vegetation	Soil	Vegetation	Soil
Woodwell and Houghton (1977)	2.5–20[a,b]		–	–
Bolin (1977)	0.8 ± 0.4	0.3 ± 0.2[b]	0.8 ± 0.4	–
Adams et al. (1977)	0.4–4.0[b]	–	–	–
Bohn (1978)	–	1–2[b]	–	–
Wong (1978)	1.5 ± 0.7	0.3 ± .02	1.5 ± 0.7	–
Woodwell et al. (1978)	1.5–13	0.5–5.0	1.0–7.0	0.25–2.5
Hampicke (1979)	1.9	0.6	1.9	0.4
Schlesinger (1978)	–	0.8[b]	–	–
Seiler and Crutzen (1980)	0 ± 2.0[a]		0.8–1.6	–
Moore et al. (1981)	2.2–4.7[a]		1.8–3.8[a]	
Houghton et al. (1983)	1.8–4.7[a]		1.3–4.2[a]	
Peng et al. (1983)	1.2[a,b]		–	–
Emanuel et al. (1984)	1.8[a,b]		–	–
Detwiler et al. (1985 and this study)	–	–	0.9–1.2	0.1–0.3

[a] Estimate cannot be separated into vegetation and soil components. Positive numbers indicate a release to the atmosphere; negative numbers indicate an uptake by the biota.

[b] Estimate cannot be separated into tropical and non-tropical component.

was 5.2 gigatons (GT; 1 GT = 10^{15} g) of carbon in 1980 (Marland and Rotty, 1983). The processes responsible for the release of CO_2 as land is cleared and cultivated are the burning and decay of vegetation and the increased oxidation of soil organic matter. Tropical forests, with their extensive areas and high rates of land use change (Myers, 1980; Seiler and Crutzen, 1980; Lanly, 1982), are the major source of this release (Table 1). The greatest uncertainty is in the size of the tropical release; thus, tropical forests and tropical land use change appear to be the appropriate focus of attention in trying to clarify the role of terrestrial ecosystems in the carbon cycle.

Working with others (Bogdonoff et al., 1985; Detwiler et al., 1985; Hall et al., 1985), I have estimated the net release of carbon from tropical vegetation using a computer model that simulates land use change in the tropics. We found that the net release from vegetation is a function of the specific land use for which an area is cleared rather than simply a function of the disappearance of forest. For example, the net release varies depending on whether the area was cleared for permanent agriculture, pasture, shifting cultivation, or timber. The computer model calculates the carbon released by clearing one hectare of primary or secondary forest for these types of land use and then multiplies the release per hectare by the number of hectares converted to each land use in that region in one year. The model estimates the release from tropical vegetation to be within the lower end of the range shown in Table 1 (Detwiler et al., 1985). To include the release from soil in the model requires a similar analysis of the per hectare changes in soil organic matter that result from the conversion of forest to each of these uses.

Methods

Three types of data are required to calculate the annual release of carbon from tropical forest soils: (1) the carbon content of the soil before clearing, (2) the changes in carbon under each land use, and (3) the area of forest converted to these uses each year. The author and others have estimated the rates of land use change (Detwiler et al., 1985), based on the work of Seiler and Crutzen (1980) and Lanly (1982). I use these estimates, with some modification, in this study. Accordingly, the following analysis focuses on the calculation of the carbon content of tropical forest soils and the changes therein after clearing. With these data, the computer model calculates the net release of CO_2 from tropical soils. A detailed description of the model can be found in Bogdonoff et al. (1985).

The carbon content of tropical forest soils

Most assessments of the carbon content of tropical forest soils estimate the storage to a depth of 1 m, assuming that it is this carbon that is in active exchange with the atmosphere (Bohn, 1976; Schlesinger, 1977; Brown and Lugo, 1982; Post et al., 1982). Although the evidence is limited, it appears that clearing and cultivation do not affect the carbon content of tropical soils to this depth. The carbon content below 25 cm of a Nigerian Alfisol was approximately the same under a 20- to 25-yr-old forest, a 10-yr-old pasture and a field which had been mechanically cultivated for 10 yr (Aina, 1979). Studies in the forest region of west Africa (Lal and Kang, 1982) found that while organic carbon declined rapidly in the surface soil after clearing and cropping using either till or no-till cultivation, the carbon content below 30 cm remained relatively unchanged. There was no change in carbon content below 15 cm 8 yr after clearing in a study of continuous cultivation in the Amazon basin of Peru (Sanchez et al., 1982; Sanchez, personal communication). In Brazil, Hecht (1982) found no significant difference in soil carbon below 60 cm in pastures with ages of 1, 5, 6, 9, 10, 12, 14 and 18 yr. Jaiyebo and Moore (1964) examined a bush fallow system of cultivation in the lowland rain forest zone of Nigeria and determined that 6 yr after clearing "pronounced differences" in soil organic matter under various crops occurred only in the top 10 cm of the soil. After 14 yr of cultivation, the surface soil (0–30 cm) under a palm plantation lost approximately 40% of the carbon it had contained under evergreen tropical forest (Ollagnier et al., 1978). The carbon loss in the subsoil (40–50 cm) was only 15%. I found no studies that indicated land use reduced soil carbon below 60 cm.

Some studies have found that soils which have been cleared of vegetation contain less carbon in the surface layers but more in the deeper layers than the undisturbed soil. Two years after an area had been cleared of evergreen forest in Trinidad, organic matter had decreased above and increased below a depth of 15 cm (Duthie et al., 1936). A 23-yr-old pasture in Costa Rica had

Table 2. Carbon stored in undisturbed forest soils by life zone

Life zone[a]	N	To 100 cm depth ($kg \cdot m^{-2}$) (a)	To 40 cm depth ($kg \cdot m^{-2}$) (b)	(b/a)
Tropical Wet Forest	23	15.0	8.1	.54
Tropical Moist Forest	163	11.4	6.5	.57
Tropical Dry Forest	184	10.2	6.0	.59
Tropical Very Dry Forest	124	6.9	5.5	.80
Tropical Thorn Woodland	2	2.6	0.9	.35
Subtropical Wet Forest	1	9.4	4.3	.46
Subtropical Moist Forest	14	9.2	5.5	.60
Subtropical Dry Forest	17	11.5	7.1	.62
Subtropical Thorn Woodland	18	5.4	3.3	.61

[a] Data provided by W.R. Emanuel, W.M. Post, A.G. Stangenberger and P.J. Zinke

less carbon in the top 40 cm of soil than an adjacent tropical semi-deciduous forest, but the pasture soil had more between 40–100 cm (Daubenmire, 1972). Kowal and Tinker (1959) found that the soil under an 11-yr-old oil palm plantation contained less carbon above 15 cm but more below 15 cm than it had under forest. Falesi et al. (1980) found that although soil under virgin forest had significantly more carbon between 0–20 cm than soil under various combinations of crops, the soil under virgin forest did not differ significantly from the soil under these crops if one compared the carbon content between 0–50 cm.

It appears from these studies that the effects of land use on soil carbon are negligible somewhere between 10–60 cm of depth, with the wide range most likely a result of differences in life zone, soil type and land use. Post et al. (1982) recorded the cumulative carbon content at 10, 20, 40, 60, 80 and 100 cm for 464 tropical and subtropical soil profiles that they examined. For this analysis, I calculated the carbon storage of tropical forest soils to a depth of 40 cm, as this appears to be the carbon pool most affected when tropical soils are converted to agriculture or pasture.

Table 2 contains the estimates of the carbon content of tropical soils to 40 and 100 cm in nine life zones. These estimates are means based on all profiles that had been subject to little or no disturbance and that could be located within a specific life zone. Between 35–80% of the carbon contained in the first meter of soil is found within the top 40 cm. Of the nine life zones for which there are data, soils in the tropical wet forest life zone contain the most carbon, and soils in the tropical thorn woodland life zone contain the least.

At present, there are no estimates of land use change for specific life zones. Brown and Lugo (1982) combined all tropical life zones into six groups along moisture and altitudinal gradients. Table 3 shows these combinations and the average carbon content of the soils within each group. The estimates of soil carbon made by Brown and Lugo (1982) also appear in Table 3. The

Table 3. Carbon stored in undisturbed forest soils by life zone group

Life zone group	To 100 cm depth ($kg \cdot m^{-2}$)	To 40 cm depth ($kg \cdot m^{-2}$)
1. TROPICAL LOWLAND WET AND RAIN FOREST		
Tropical rain forest[a]	18.0	9.7
Tropical wet forest	15.0	8.1
Average	16.5 (11.5)[b]	8.9
2. TROPICAL LOWLAND MOIST FOREST		
Tropical moist forest	11.4	6.5
Average	11.4 (8.5)[b]	6.5
3. TROPICAL LOWLAND DRY FOREST		
Tropical dry forest	10.2	6.0
Tropical very dry forest	6.9	5.5
Tropical thorn woodland	2.6	0.9
Average	6.6 (7.1)[b]	4.1
4. SUBTROPICAL AND TROPICAL WET AND RAIN FOREST		
Subtropical rain forest[a]	18.0	8.3
Subtropical wet forest	9.4	4.3
Montane rain forest[a]	20.0	9.2
Montane wet forest[a]	16.0	7.4
Average	15.9 (17.5)[b]	7.3
5. SUBTROPICAL AND TROPICAL MOIST FOREST		
Subtropical moist forest	9.2	5.5
Montane moist forest[a]	12.0	7.2
Average	10.6 (9.8)[b]	6.4
TROPICAL CLOSED FOREST (Life zone groups 1–5 weighted by area)	12.3	6.7
6. SUBTROPICAL AND TROPICAL DRY FOREST		
Subtropical dry forest	11.5	7.1
Subtropical thorn woodland	5.4	3.3
Average	8.5 (3.9)[b]	5.2
TROPICAL OPEN FOREST (Life zone group 6)	8.5	5.2

[a] The data of Post et al. (1982) contained no profiles for these life zones. Estimates of carbon storage to 100 cm in these life zones were interpolated from Fig. 1 in Post et al. (1982). The estimates for 40 cm depth were calculated by multiplying the 100 cm estimate by the ratio of the 40 cm estimate to the 100 cm estimate for life zones in the same group for which there were data (see Table 2). Life zones grouped according to Brown and Lugo (1982).

[b] Values in parentheses are Brown and Lugo's (1982) estimates for the life zone group to 100 cm depth.

estimates of soil carbon to a depth of 1 m from the present study and from Brown and Lugo (1982) are roughly similar except for tropical lowland wet and rain forest and for subtropical and tropical dry forest. Brown and Lugo

(1982) had no data for subtropical and tropical dry forest soils and estimated their carbon content from regression equations. Soils of the tropical lowland wet and rain forest group contain the most carbon, with an average of 16.5 kg $\cdot$ m^{-2} to a depth of 1 m and 8.9 kg $\cdot$ m^{-2} to a depth of 40 cm. Soils with the least carbon are found in the tropical lowland dry forest group. They contain 6.6 kg $\cdot$ m^{-2} of carbon in the first meter of depth and 4.1 kg $\cdot$ m^{-2} in the first 40 cm.

While it has been possible to estimate land use change by life zone group for some countries (see Hall et al., 1985), it has not been possible to make similar estimates for the entire tropics. The two studies of land use (Seiler and Crutzen, 1980; Lanly, 1982) on which we based our analysis of the role of tropical vegetation in the carbon cycle (see Detwiler et al., 1985) divided all tropical forests into only two types: closed and open. To use these assessments of land use here requires a further aggregation of the estimates of soil carbon. According to Brown and Lugo (1982), tropical closed forest comprises the first five life zone groups listed in Table 3, while tropical open forest is equivalent to the subtropical and tropical dry forest group. Therefore, I calculated the soil carbon content of closed forest as the average of the estimates for the five life zone groups, weighted by the area of each group as given by Brown and Lugo (1982). For the carbon content of open forest soil, I used the value for the subtropical and tropical dry forest group (Table 3). The soils of tropical closed forests have about 6.7 kg $\cdot$ m^{-2} of carbon within the zone affected by land use change; soils of tropical open forests have about 5.2 kg $\cdot$ m^{-2} of carbon within that zone.

The changes in the carbon content of forest soils following clearing

The carbon content of a soil under agricultural use may decline for a number of reasons: erosion, removal of topsoil by mechanical clearing and increased oxidation of organic matter. Only the last of these processes directly affects the CO_2 content of the atmosphere. The fate of carbon carried away by erosion or clearing is unknown, but it seems unlikely that all of it is converted immediately to CO_2 (see Zinke et al., 1978). Bulldozers can remove large amounts of topsoil if operated carelessly (Van der Weert, 1974; Seubert et al., 1977; Uhl et al., 1982). Therefore, any estimate based on changes in soil carbon in situ is probably an overestimate of the CO_2 released. As it would be extremely difficult to determine the rate of erosion or the fate of the eroded material, I assume that all the soil carbon that has disappeared after clearing has entered the atmosphere. Since most of the carbon probably is lost through increased decomposition rather than erosion (Schlesinger, 1984), estimates based on this assumption are realistic, although not precise.

Determining the change in a soil's carbon content involves several problems. The most common sampling procedure is to take a soil core to a certain depth and determine the percent carbon by weight of the entire core. This procedure makes it difficult to calculate the losses due to land use change. First, there is seldom any attempt to determine whether the sampling depth chosen includes the entire zone affected by the change in land use. Second, bulk density often is not reported, which prevents the conversion of changes in percent carbon to weight of carbon lost per unit area of soil, the appropriate measure of the effect of agriculture in the context of the global carbon cycle (Schlesinger, 1977). Third, comparing percent carbon before and after disturbance overestimates the loss of soil carbon if significant soil compaction occurs after clearing.

Samples taken from compacted cultivated soil will include "subsoil" not sampled when the soil was undisturbed. Because the carbon concentration of most soils decreases with depth, the inclusion of this subsoil in the cultivated soil sample gives the appearance that the carbon content of the cultivated soil has decreased more than it actually has. Conversely, if one compares the weight of carbon contained within the soil volumes sampled before and after clearing, the inclusion of a greater mass of soil within the volume sampled after clearing due to soil compaction may give the impression that the carbon content of the cultivated soil has increased. Table 4 illustrates the problems in determining changes in the carbon content when soil is significantly compacted after clearing. As soil compaction is a frequent consequence of forest clearing in the tropics (Popenoe, 1957; Juo and Lal, 1977; Aina, 1979; Aweto, 1981; Hecht, 1982; Glubczynski, 1983), especially when the vegetation is cleared mechanically (Van der Weert, 1974; Seubert et al., 1977; Lal and Cummings, 1979), the problem is not insignificant. The difficulty caused by changes in bulk density can be overcome by sampling equivalent weights of soil (Ayanaba et al., 1976). Although Nye and Greenland (1964) recognized the problem caused by changes in bulk density, of the many studies examined for this analysis, only those by Ayanaba et al. (1976) and Glubczynski (1983) discussed it or attempted to correct for it.

The final difficulty in determining the change in the carbon content of a soil is that this change does not occur instantaneously. Although some studies (Krebs, 1975; Sanchez et al., 1982) indicate that the greatest change occurs in the first year after clearing, others indicate that the carbon content may continue to decrease for 5–10 yr afterwards (Brams, 1971; Aina, 1979; Lal and Kang, 1982; Brown et al., 1984).

In light of these difficulties, I calculate the change in soil carbon as the change in percent carbon over time. While this method overestimates the decline in carbon due to land use, its use increases the number of studies available for analysis, as many studies do not include bulk density. More importantly, using the change in percent carbon rather than the change in the weight of soil carbon produces estimates of the net release of CO_2 from tropical soils that are probably too high rather than too low. If the estimated release from tropical soils is small even when calculated in this manner, it would indicate that these soils contribute a relatively small amount of CO_2 to the atmosphere compared to the release from the destruction of tropical

Table 4. Calculating changes in soil carbon storage due to land use; the problem caused by changes in bulk density. Data for maize from Juo and Lal (1977); data for pasture from Hecht (1982).

	Vegetation	Time since clearing	Depth of samples	Bulk density ($g \cdot cm^{-3}$)	%C	$gC \cdot m^{-2}$	Δ%C[a]	$\Delta gC \cdot m^{-2}$[a]
Initial conditions before clearing	Secondary forest	–	15 cm	1.00	1.74	2610	–	–
Conditions after land use	Maize without crop residue returned	3 yr	15 cm	1.59	1.10	2624	–37	+1
	Maize with crop residue returned	3 yr	15 cm	1.46	1.58	3460	–9	+33
Initial conditions before clearing	Virgin forest	–	30 cm	0.6	1.3	2430	–	–
Conditions after land use	Pasture	18 yr	30 cm	1.2	0.8	2880	–38	+23

[a] Δ%C and $\Delta gC \cdot m^{-2}$ calculated as (final value ÷ initial value ×100) – 100

vegetation or the burning of fossil fuels.

To allow comparisons among soils whose carbon content before clearing may differ greatly, the change is calculated as:

$$\Delta C = 100 - \left(\frac{\% C_T}{\% C_O} \times 100 \right)$$

where $\% C_T$ = percent carbon at T years after clearing and $\% C_O$ = percent carbon before clearing. The release of carbon per unit area is then calculated by multiplying the percent reduction of each land use by the estimates of carbon stored in the soil. I include only those studies that contain: (1) an estimate of soil carbon content before clearing (either from samples taken before clearing, or, more frequently, from samples taken from nearby undisturbed soils; (2) an estimate of soil carbon after clearing and use; (3) the type of use; and (4) the duration of use. Observations of soil carbon in areas that were cleared but not used for agriculture or pasture were not included (see, for example, Cunningham, 1963).

Tropical forests are cleared for permanent agriculture, swidden agriculture, pasture and timber (Seiler and Crutzen, 1980; Lanly, 1982). All of these land uses start with cutting and, with the exception of logging, burning of the felled vegetation in situ. The burning itself has only a slight effect on the soil's carbon content. During the fire, temperatures may exceed 600 °C 1–2 cm above the surface soil; but 3 cm below the surface, temperatures do not appear to exceed 70 °C except under concentrated piles of fuel (Zinke et al., 1978; Ewel et al., 1981). After the burn, the carbon content of the soil may actually exceed that of the soil before clearing (Nye and Greenland, 1964; Seubert et al., 1977; Lal and Cummings, 1979). In several studies, areas cleared and allowed to revegetate naturally rather than being put to agricultural use had more carbon in the soil than they did before clearing (Harcombe, 1977; Juo and Lal, 1977; Swaine and Hall, 1983; Uhl and Jordan, 1984). Thus, it appears that the decrease in soil carbon is a result of the soil's use, not its clearing. Glubczynski (1983) found that the soil under tropical secondary forest sites that had been selectively logged until about 1953 contained more carbon than the soil under nearby undisturbed forest. Clear cutting appears to have little effect on the carbon content of temperate forest soils (Gholz and Fisher, 1982; Edwards and Ross-Todd, 1983; Hendrickson et al., 1985). Accordingly, I have assumed that selective logging in the tropics does not decrease soil carbon. The estimate of the area logged annually in the tropics, given in Table 5, is for selective logging, in which removals can be as few as 1–3 trees per hectare (see Detwiler et al., 1985). Timber salvage operations, which often occur on areas cleared for new pastures or agricultural fields (see Seubert et al., 1977; Ewel et al., 1981; Silva, 1981), are not included in the estimate of logging activity as these operations are incidental to the conversion of forest to these other uses (Lanly, 1982).

Many studies indicate that although the carbon content of forest soils

Table 5. Tropical closed forests: rates of land use change, 1980

	Seiler and Crutzen (1980) (10^6 ha • yr^{-1}) Low	High	Lanly (1982) (10^6 ha • yr^{-1})
Primary forest to permanent use:			
To pasture	1.6	1.4	2.5
To agriculture and roads	0.3	2.2	2.3[a]
Primary forest to logged secondary forest	–	–	3.7
Secondary forest to permanent use:			
To pasture	0.5	1.5	–
To agriculture	0.6	0.8	–
Primary forest to swidden agriculture due to migration of shifting cultivators	0.5	1.5	–
Primary forest to swidden agriculture due to population increase of shifting cultivators	2.6	2.9	3.4
Secondary forest to swidden agriculture	15.5	40.6	18.0

[a] Includes 0.7 × 10^6 ha cleared for logging roads

decreases after clearing and cultivation, it eventually approaches a new, albeit lower, equilibrium (Jenny, 1941; Nye and Greenland, 1960; Brams, 1971; Lal and Kang, 1982; Sanchez et al., 1982). It also appears that the carbon content of cleared forest soils returns to that of undisturbed soil if there is a sufficient period of forest fallow (Nye and Greenland, 1960; Aweto, 1981; Glubczynski, 1983; Brown et al., 1984). In order to determine the equilibrium carbon content of tropical forest soils used for agriculture or pasture, I fit a spline curve to the data for each of these land uses. The first section of the curve represents the period during which the carbon content of the soil declines; the second section represents the equilibrium level. The spline model predicts the soil's carbon content at equilibrium under the new land use and the time required for a soil previously supporting forest to reach equilibrium. The spline model for the changes in carbon content under forest fallow is somewhat different. I assume that the soil returns to its carbon content under primary forest. The model, using the data for forest fallow soils, predicts the number of years necessary for the soil to return to its original carbon content and the content at the time of abandonment.

The data on changes in soil carbon and their sources are found in the appendix. Table A contains the data for forest soils that were converted to agricultural fields, either permanently or temporarily. Changes in the carbon content of forest soils cleared for pasture are given in Table B. Table C presents the data on changes in forest soils that were cleared, used for pasture or agriculture, and then abandoned. This table contains data only from fallow sites with "natural" secondary forest: studies comparing soils under older forests with soils under plantations were not included.

The data for changes in the carbon content of cultivated soils over time and the spline curve with the least squares fit appear in Figure 1. The spline

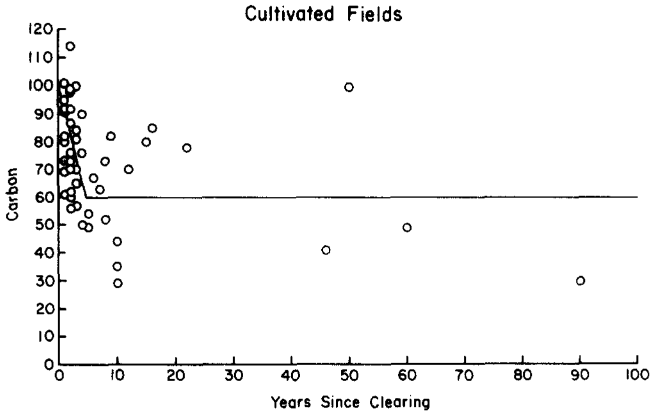

Figure 1. The change in the carbon content of forest soils under cultivation. The original carbon content before clearing = 100.

function predicts an equilibrium carbon storage of 60% of the amount found in forest soils, reached after 5 yr of cultivation. The spline model explains 20.4% of the variance in the data. Figure 2 shows the data for pasture soils. In this case; a spline curve fits the data less well than does a curve equal to the mean of the data, indicating that the carbon content of pasture soils is independent of the pasture's age. The data show that, on average, forest soils used for pasture lose about 20% of their carbon. The spline curve for soils under forest fallows is shown in Figure 3. The function producing this curve predicts a carbon content at abandonment equal to 73% of the carbon found in the soil of primary forests and a fallow period of 35 yr before the carbon content returns to its original value. The spline model explains 23.3% of the variance found in these data.

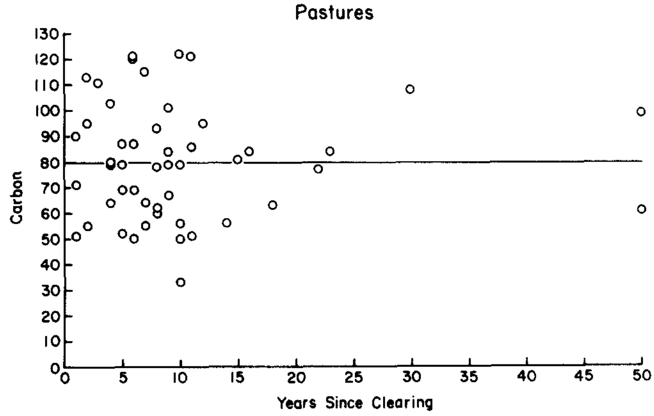

Figure 2. The change in the carbon content of forest soils under pasture. The original carbon content before clearing = 100.

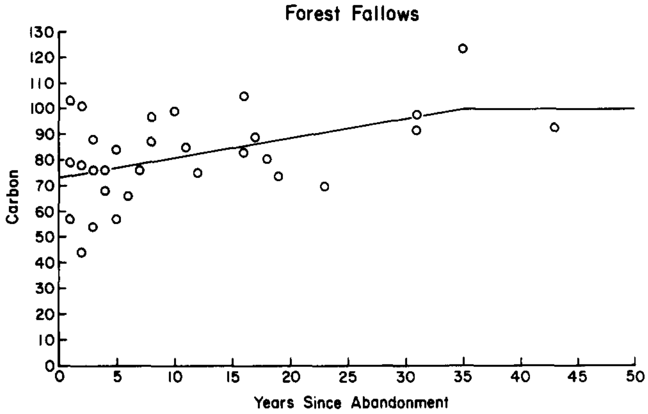

Figure 3. The change in the carbon content of forest soils that have been used for agriculture or pasture and then abandoned. The original carbon content before clearing = 100.

These estimates of the change in soil carbon, combined with the estimates of the carbon stored in the soil of undisturbed forests, allow the estimation of the carbon content of forest soils used for permanent agriculture,,pasture and shifting cultivation. After 5 yr of cultivation, closed forest soils contain 4.0 kg C • m^{-2}; open forest soils contain 3.1 kg C • m^{-2}. Closed forest soils converted to pasture have a carbon content of 5.4 kg • m^{-2}, while open forest soils have 4.2 kg • m^{-2}.

There are two ways to calculate the carbon content of forest soils after the first two years of shifting cultivation. The spline model for cultivated soils predicts that after two years of cultivation, forest soils have lost 18% of their carbon (Figure 1). The model for soils under forest fallow indicates that they have lost 27% by the time they are abandoned (Figure 3). The reduction predicted from the data for fallow soils may be greater since some of these were cultivated for more than two years before abandonment (see, for example, Falesi et al., 1980). Continuing the bias towards overestimating rather than underestimating the release of CO_2 from tropical soils, the carbon content of soils subject to shifting cultivation will be calculated as 73% of that under undisturbed forests, which yields estimates of 4.9 kg C • m^{-2} for closed forest soils and 3.8 kg C • m^{-2} for open forest soils at the time they are abandoned.

The changes in land use

There are two estimates of land use change in tropical closed and open forests: Seiler and Crutzen (1980) and Lanly (1982). Both distinguish between clearing for shifting cultivation and clearing for permanent agriculture or pasture, a distinction that is critical since the increase in the carbon storage of vegetation and soil during the fallow period reduces the net CO_2 release from forest

Table 6. Tropical open forest: rates of land use change, 1980

	Seiler and Crutzen (1980) (10^6 ha • yr^{-1}) Low	High	Lanly (1982) (10^6 ha • yr^{-1})
Primary forest to permanent use:			
To pasture	1.7	2.1	1.3
To agriculture	0.2	3.0	0.8
Primary forest to swidden agriculture	–	–	1.7
Secondary forest to permanent use:			
To pasture	1.0	1.0	–
To agriculture	0.2	1.4	–
Secondary forest to swidden agriculture	8.1	24.3	18.6

clearing (Hall et al., 1985). I have used these studies, with some modifications, to estimate the release from vegetation (Detwiler et al., 1985). Because forest soils used for permanent cultivation lose twice as much carbon as those used for pasture, I have further modified these estimates so as to differentiate between clearing for these two uses.

Seiler and Crutzen (1980) estimate that 4.8–6.0 million ha of tropical forest were cleared annually for pasture from 1960 to 1975. Between 0.5–1.5 million ha of this clearing occurred in secondary closed forest. They do not explicitly apportion the remaining 4.3–4.5 million ha of annual clearing among primary closed forest, primary open forest and secondary open forest. Their low estimate, 4.3 million ha, equals 86% of the permanent clearing in these three types of forest, so it was assumed that this percentage of the permanent clearing in each type of forest was for pasture. Similarly, in the high estimate of Seiler and Crutzen, 4.5 million ha constitutes 41% of the permanent clearing in these forests, and the clearing for pasture was apportioned accordingly. Lanly (1982) gave no separate estimate of the clearing for pasture. According to his study, clearing for pasture and agriculture was 4.2 million ha per year in closed forests and 2.1 million ha per year in open forests. The assessments of Seiler and Crutzen indicate that clearing for pasture constitutes 41–86% of all permanent clearing; therefore I assume that 60% of Lanly's estimates of permanent clearing was for pasture. The rates of land use change appear in Tables 5 and 6.

These three sets of data – the carbon content of undisturbed tropical forest soils; the changes in that content resulting from the use of these soils for agriculture, pasture and shifting cultivation; and the rates of land use change – allow our model to estimate the annual net release of carbon from tropical soils (see Bogdonoff et al., 1985). Because there are three estimates of land use change for both open and closed forests, the model predicts a range of CO_2 releases from tropical soils that vary according to the differences in these estimates of forest clearing.

Table 7. Annual net release of carbon from tropical soils, 1980

	Open forest soils ($GT \cdot yr^{-1}$)	Closed forest soils ($GT \cdot yr^{-1}$)
Rates of land use change from Seiler and Crutzen (1980):		
High estimate	0.083[a]	0.160
Low estimate	0.015	0.092
Rates of land use change from Lanly (1982)	0.062	0.173

[a] Three significant figures are included to allow comparison among estimates and do not reflect the degree of accuracy in the estimates.

Results

According to the model and the data, the release of carbon from tropical soils was 0.11–0.26 GT in 1980 (Table 7). The release from soils in closed forest regions accounted for 0.092–0.173 GT; the release from open forest soils was 0.015–0.083 GT. Seiler and Crutzen's high estimate of forest clearing produced the largest release of carbon from open forests; Lanly's estimate of clearing produced the largest release from closed forests.

Discussion

The principal reason that the estimates of the net release of carbon from tropical soils is significantly smaller than the net release from vegetation is that there is less carbon in the soil than in the vegetation of closed forests. Open forests contain 40 tons $C \cdot ha^{-1}$ in their vegetation (Brown and Lugo, 1982) and 52 tons $C \cdot ha^{-1}$ in their soil (Table 3); closed forests have 164 tons $C \cdot ha^{-1}$ in their vegetation (Brown and Lugo, 1982) but only 67 tons $C \cdot ha^{-1}$ in their soil. Because most of the clearing takes place in closed forests, the difference between the carbon storage of the soil and the vegetation in this forest type accounts for the large differences in the respective releases. If I had used the estimates of carbon stored in the soil to a depth of 1 m rather than to 40 cm, the net release from soils would have been almost twice as large. According to Brown and Lugo (1982), the soils of undisturbed tropical forests, covering 1,838 million ha, contain 159 GT of carbon. Post et al. (1982) estimate this pool at 314 GT, based on a forest area estimate of 3,940 million ha. If one assumes that the soil carbon pool with the potential to affect the global carbon cycle in the near future extends to 40 cm rather than 1 m, these estimates are reduced to 114 and 149 GT, respectively.

Another reason that the release from soils is less than that from vegetation is that land use change does not have as severe an impact on the soil as on the vegetation. In areas cleared for pasture and permanent agriculture, at least 85% of the carbon in the forest vegetation eventually enters the atmosphere

Detwiler et al., 1985). The present study found that soils cleared for agriculture lose 40% of their carbon, those cleared for shifting cultivation lose 18–27% and those cleared for pasture 20%. It was assumed that the amount of soil carbon remains constant in forests cut for timber. Other studies of the role of terrestrial ecosystems in the global carbon cycle have used similar values for the changes in soil carbon after clearing. Houghton et al. (1983) assumed that tropical forest soils converted to agriculture lose 50% of their carbon, those cleared for pasture lose 25% and those cleared in timber harvesting lose 35%. They did not include shifting cultivation in their analysis. Only their estimate for the loss that occurs after logging is greatly different from the ones used in this analysis.

Among the studies cited in Tables A–C, there is a large amount of variation in the changes that occur in soil carbon after clearing. The spline curves fit by least squares methods explain about 20% of the variation in the data for fallow and agricultural soils. Although the predictive ability of these spline models is limited, this is to be expected because age is the only variable in the models. Other factors affect the carbon content of disturbed soils. Allen (1985) found that the decline in organic matter after disturbance was 50% greater for tropical soils developed on old parent material. The method of clearing (Seubert et al., 1977; Lal and Cummings, 1979), tillage (Aina, 1979; Lal and Kang, 1982), crop rotation (Falesi, 1976) and mulching regimes (Ayanaba et al., 1976; Juo and Lal, 1977) influence the loss of organic matter in tropical soils under cultivation. Cropping intensity and soil type affect the rate at which soil carbon increases in forest fallow (Nye and Greenland, 1960). At present, assessments of land use in the tropics do not differentiate among such factors as soil type, clearing method and crop rotation, and it is doubtful that these assessments will achieve this degree of specificity in the future. Thus it is not particularly useful to determine the effect these factors have on the decline of organic matter in assessing the role of tropical soils in the global carbon cycle. Brown et al. (1984) found that changes in soil carbon varied according to climate as well as land use. The development of separate models of soil carbon changes for each life zone group might reduce some of the variation not explained by the models presented here and it is possible to estimate land use change by life zone group for some tropical countries (Hall et al., 1985).

Individual studies that observed the changes in soil carbon at one site over several years indicate that agricultural soils do reach an equilibrium carbon content after some period of time and support the conclusion of this analysis that the carbon content of these soils stabilizes at approximately 60% of the level under forest after 5 yr of cultivation. Brams (1971) reported that two west African soils reached a stable carbon content equal to half that present before clearing when cultivated for 5 yr. Lal and Kang (1982) also reported an equilibrium level of about 50%, but reached after 3.5 yr of cultivation. Sanchez et al. (1982) found that after 1 yr of cultivation, soil carbon had declined by 27%; it then remained constant for 7 yr. Studies of pasture soils, however, have found large variation in soil carbon after clearing and do not support the conclusion that these soils reach an equilibrium after clearing (Falesi, 1976; Hecht, 1982). It may be that differences in stocking rates, weeding frequency and duration of actual use are more important than age in determining the carbon content of pasture soils (see Hecht, 1982; Buschbacher et al., 1984).

The studies of fallow soils that investigated a number of sites with different ages (Cowgill, 1961; Turenne, 1977; Aweto, 1981) indicate that soil organic matter increases under secondary forest. The spline model for these soils predicts that their carbon content will equal that of primary forest soils about 35 yr after abandonment. Because the fallow period averages 10–20 yr in closed forest and 6–12 yr in open forest, it is unlikely that the carbon content of soils cleared for shifting cultivation will return to that of undisturbed soils. Myers (1984) reports that the length of the fallow period is decreasing in many areas of the tropics, with the result that shifting cultivation will eventually become permanent cultivation in these areas. The soil has less time to recover as the fallow period decreases and its carbon content will approach that under permanent agriculture.

The release of carbon from tropical soils is small compared with the release from tropical vegetation and from fossil fuels. The burning and decay of tropical vegetation cleared during the conversion of forests to fields and pastures released 0.9–1.2 GT of carbon in 1980 (Detwiler et al., 1985). This estimate of the release from vegetation takes into account the uptake of CO_2 by recovering secondary forest, but not the possible uptake by mature vegetation due to CO_2 fertilization (see Lemon, 1977). The combustion of fossil fuels injected another 5.2 GT in the same year (Marland and Rotty, 1983). I believe that it is unlikely that the actual release from tropical soils is much different from the estimate of 0.1–0.3 GT calculated in this analysis. For the release to be appreciably larger from forest soils converted to pastures or agricultural fields, one must assume that land use in general affects soil carbon to a depth significantly greater than 40 cm, or that changes in soil carbon caused by land use are much greater than calculated here, or both. The change in soil carbon was determined from changes in percent carbon, which overestimate the decrease caused by land use if bulk density increases after clearing. For the total release to be significantly larger than the results of this analysis, it is necessary that forest clearing in 1980 was much greater than the high estimates of Seiler and Crutzen (Tables 5 and 6). Although much uncertainty exists concerning the rates of forest clearing in the tropics (Myers, 1980, 1984), the three assessments of land use change are similar in their estimates of permanent clearing, which is responsible for the bulk of the carbon release. The general agreement among these assessments makes it unlikely that the actual clearing rates for 1980 are far outside this range. Forest clearing in the tropics may have increased significantly since 1980 (Melillo et al., 1985).

For the release from soils to be smaller than calculated here, one must assume that the conversion of forest soils to cultivated fields and pastures has little effect on soil carbon. Because the uncertainties involved in estimating the change in soil carbon after clearing were resolved so as to overestimate the change, it is possible that the total release in 1980 from tropical soils was less than 0.1 GT if tropical forests were cleared at rates near the low estimate of Seiler and Crutzen (1980; Tables 5 and 6). The data upon which they based their estimates applied to the period 1960–1975. As it is reported that the clearing of tropical forests has accelerated in the last decade (Myers, 1980, 1984), I believe that the actual rates of clearing are closer to the high estimate of Seiler and Crutzen (1980) and the estimate of Lanly (1982). Therefore, it is unlikely that the release was much lower than 0.11 GT in 1980, as the underestimation of the rates of land use change probably compensates for the overestimation of the decrease in soil carbon after clearing.

Some have suggested that agricultural soils act as a sink for atmospheric CO_2 as a result of improved cultivation, increased return of crop residues to the soil and greater use of nitrogen fertilizers (Lemon, 1976; Loomis, 1979). The data for agricultural soils in the tropics do not support this conclusion (Table A). Although the practices cited above may reduce the loss of soil organic matter (Ayanaba, 1976; Aina, 1979; Lal and Kang, 1982), the net effect of clearing and cultivating tropical soils is to decrease their carbon content. The irrigation of desert soils does increase their carbon content (Schlesinger, 1982), but the area under irrigation in the tropics appears to be insignificant in the context of the carbon cycle (Houghton et al., 1983).

In conclusion, the clearing of tropical forest soils produces a small but significant release of CO_2 to the atmosphere. The annual release in 1980 was 0.11–0.26 GT of carbon, equivalent to 2–5% of the carbon released from the combustion of fossil fuels. Added to the 0.9–1.2 GT released from cleared vegetation, the total net release from tropical ecosystems due to land use change was 1.0–1.5 GT of carbon in 1980. The total net release from all terrestrial ecosystems in 1980, calculated from changes in the $^{13}C/^{12}C$ ratio of the atmosphere as recorded in the annual growth rings in trees, was 1.2–1.8 GT (Peng et al., 1983; Emanuel et al., 1984). Thus, it appears that most, if not all, of the present release from forests and soils occurs in the tropics.

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Appendix

Table A. Changes in the carbon content of forest soils under cultivation

Reference	Years since clearing	Depth[a] (cm)	%C	Δ%C
Duthie et al. 1936				
'Natural forest'	–	0–30	1.19	–
Crops[b]	2		0.99	–27%
Fauck 1956				
'Old savanna woodland'	–	0–15	0.75	–
Crops	6		0.50	–33%
Popenoe 1957				
'Virgin rain forest'	–	0–40	7.50	–
Crops	1		4.57	–39%
Cowgill 1961				
'Climax lowland tropical forest'	25	0–15	5.09	–
Crops	1		4.16	–18%
	2		3.88	–24%
Nye and Greenland 1964				
'Moist semideciduous tropical forest'	50	0–30	1.01	–
Crops	1		1.02	+ 1%
	2		1.00	– 1%
Brams 1971				
'Secondary forest'	20	2.5–18	2.03	–
Crops	2		1.22	–40%
	5		1.10	–46%
'Bush'	6	2.5–18	5.99	–
Crops	2		4.19	–30%
	5		2.94	–51%
Watters and Bascones 1971				
'Second growth rain forest'	15–30	0–30	2.68	–
Crops	1		2.47	– 8%
	2–3		2.67	0%
Siband 1972				
'Tropical dry forest'	–	0–10	1.65	–
Crops	3		1.38	–16%
	12		1.16	–30%
	46		0.68	–59%
	90		0.50	–70%
Krebs 1975				
'Natural forest'	–	0–30	4.45	–
Crops	4		4.01	–10%
	9		3.66	–18%
	15		3.55	–20%
	16		3.79	–15%
	22		3.46	–22%
Ayanaba et al. 1976				
'Bush regrowth'	?	0–20[c]	1.11	–
Crops	2		1.27	+14%
'Bush regrowth'	?	0–20[c]	1.43	–
Crops	2		0.88	–38%

Table A, continued

Reference	Years since clearing	Depth (cm)	%C	Δ%C
'Bush regrowth'	?	0–20^{c}	0.89	–
Crops	2		0.50	–44%
'Bush regrowth'	?	0–20^{c}	1.22	–
Crops	2		1.19	– 2%
Feller and Milleville 1977				
'Virgin open forest'	–	0–20	0.37	–
Crops	2		0.34	– 8%
	3		0.30	–19%
Turenne 1977				
'Primary forest'	–	10–20	1.13	–
Crops	1		1.07	– 5%
Seubert et al. 1977				
'Secondary moist tropical forest'	17	0–50	0.76	–
Crops	1		0.69	– 9%
'Secondary moist tropical forest'	17	0–50	0.75	–
Crops	1		0.52	–31%
Juo and Lal 1977				
'Secondary forest'	10–15	0–15	1.74	–
Crops	3		1.22	–30%
Aina 1979				
'Secondary bush fallow'	20–25	0–15	2.21	–
Crops	10		0.64	–71%
'Secondary bush fallow'	15–20	0–10	2.44	–
Crops	10		0.85	–65%
Falesi et al. 1980				
'Virgin forest'	–	0–50	0.54	–
Crops	1		0.49	–81%
Lal and Kang 1982				
'Secondary forest'	?	0–15	2.30	–
Crops	1.5		2.00	–13%
	2		1.60	–30%
	2.5		1.50	–35%
	3		1.30	–43%
	3.5		1.15	–50%
	7		1.45	–37%
	8		1.20	–48%
Sanchez et al. 1982				
'Secondary humid tropical forest'	17	0–15	1.24	–
Crops	1		0.90	–27%
	8		0.90	–27%
Glubczynski 1983				
'Mature subtropical wet forest'	–	0–50	2.86	–
Crops	1		2.29	–20%
	10		1.26	–56%
'Mature subtropical moist forest'	–	0–25	1.39	–
Crops	3–5		1.06	–24%

Table A, continued

Reference	Years since clearing	Depth (cm)	%C	Δ%C
Crops	50		1.39	0%
'Mature subtropical dry forest'	–	0–25	3.46	–
Crops	60		1.71	–51%

[a] When percent carbon was measured between several depth intervals, the average value for the intervals whose total depth was closest to 40 cm was used.

[b] The percent carbon values for plots cultivated for the same length of time but planted with different crops were averaged.

[c] Ayanaba et al. sampled equivalent weights of soil. The depth of their samples varied between 15–20 cm.

Table B. Changes in the carbon content of forest soils under pasture

Reference	Years since clearing	Depth[a] (cm)	%C	Δ%C
Bruce 1965				
'Virgin tropical rain forest'	–	0–15	4.13	–
Pasture	8		3.26	–22%
	11		3.80	–14%
	16		3.48	–16%
	22		3.20	–23%
Daubenmire 1971				
'Tropical semi-deciduous forest'	–	0–40	2.76	–
Pasture	23		2.33	–16%
Krebs 1975				
'Natural forest'	–	0–30	4.45	–
Pasture	4		3.55	–20%
	15		4.05	– 9%
Falesi 1976				
'Semi-deciduous equatorial forest'	–	0–20	1.13	–
Pasture	1		0.58	–49%
	2		0.62	–45%
	4		0.72	–36%
	5		0.59	–48%
	6		0.56	–50%
	7		0.62	–45%
	8		0.70	–38%
	9		0.76	–33%
	10		0.57	–50%
	11		0.58	–49%
'Humid evergreen tropical forest'	–	0–20	0.68	–
Pasture	1		0.61	–10%
	2		0.77	+13%
	4		0.70	+ 3%
	5		0.54	–21%
	6		0.82	+21%
	7		0.78	+15%

Table B, continued

Reference	Years since clearing	Depth (cm)	%C	Δ%C
	8		0.63	− 7%
	9		0.69	+ 1%
	10		0.54	−21%
'Humid evergreen tropical forest'	–	0–20	1.62	–
Pasture	3		1.80	+11%
	4		1.28	−21%
	5		1.11	−31%
	6		1.11	−31%
	7		1.03	−36%
	8		0.98	−40%
	9		1.36	−16%
	11		1.96	+21%
Aina 1979				
'Secondary forest'	15–20	0–10	2.09	–
Pasture	10		2.56	+22%
Falesi et al. 1980				
'Virgin humid tropical forest'	–	0–50	0.54	–
Pasture	4–7		0.65	+20%
Hecht 1982				
'Virgin humid tropical forest'	–	0–30	1.26	–
Pasture	1		0.90	−29%
	2		1.20	− 5%
	5		1.10	−13%
	6		1.10	−13%
	9		1.00	−21%
	10		0.70	−44%
	12		1.20	− 5%
	14		0.70	−44%
	18		0.80	−37%
Glubczynski 1983				
'Mature subtropical wet forest'	–	0–50	2.86	–
Pasture	10		0.95	−67%
	50		1.75	−39%
'Mature subtropical wet forest'	–	0–50	2.33	–
Pasture	50		2.30	− 1%
'Mature subtropical moist forest'	–	0–50	1.10	–
Pasture	30		1.19	+ 8%

[a] When percent carbon was measured between several depth intervals, the average value for the intervals whose total depth was closest to 40 cm was used.

Table C. Changes in the carbon content of forest soils under forest fallow

Reference	Years since abandonment	Depth[a] (cm)	%C	Δ%C
Reed 1951				
'Virgin forest'	–	0–15	2.50	–
Forest fallow	8–15		1.88	–25%
Popenoe 1957				
'Virgin rain forest'	–	0–40	7.50	–
Forest fallow	1–2		3.33	–56%
	3–5		5.09	–32%
Cowgill 1961				
'Climax lowland tropical forest'	25	0–15	5.09	–
Forest fallow	1		4.02	–21%
	2		3.96	–22%
	3		4.48	–12%
	4		3.88	–24%
	5		4.28	–16%
	6		3.35	–34%
	8		4.41	–13%
	10–12		4.31	–15%
Watters and Bascones 1971				
'Second growth rain forest'	15–30	0–30	2.68	–
Forest fallow	2		2.70	+ 1%
De las Salas and Fölster 1976				
'Primary seasonal evergreen forest'	–	0–10	2.10	–
Forest fallow	3		1.60	–24%
	16		2.20	+ 5%
Turenne 1977				
'Primary forest'	–	0–10	1.49	–
Forest fallow	1		1.54	+ 3%
'Primary forest'	–	10–20	1.29	–
Forest fallow	19		0.96	–26%
'Primary forest'	–	10–20	1.63	–
Forest fallow	31		1.60	– 2%
Falesi et al. 1980				
'Virgin forest'	–	0–50	0.54	–
Forest fallow	5–10		0.52	– 4%
	15–20		0.44	–19%
Aweto 1981				
'Mature moist evergreen tropical forest'	–	0–30	2.70	–
Forest fallow	1		1.54	–43%
	3		1.45	–46%
	7		2.06	–24%
	10		2.67	– 1%
Raich 1983				
'Mature tropical premontane wet forest'	–	0–50	2.82	–
Forest fallow	17		2.50	–11%
Glubczynski 1983				
'Mature subtropical wet forest'	–	0–50	2.33	–

Table C, continued

Reference	Years since abandonment	Depth (cm)	%C	Δ%C
Forest fallow	20–25		1.62	–30%
	38–47		2.17	– 7%
'Mature subtropical dry forest'	–	0–25	1.39	–
Forest fallow	5		0.79	– 3%
'Mature subtropical dry forest'	–	0–25	3.46	–
Forest fallow	35		4.29	+24%
Werner 1984				
'Mature tropical wet forest'	–	0–10	4.65	–
Forest fallow	16		3.88	–17%
	31		4.26	– 8%

[a] When percent carbon was measured between several depth intervals, the average value for the intervals whose total depth was closest to 40 cm was used.