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THE EFFECTS OF LAND USE ALTERATION ON TROPICAL CARBON EXCHANGE

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ABSTRACT

The net annual release of carbon from tropical forests of the world is estimated to range from 0.6 to 1.1 x 10^9 tons (Gt), based on computer model simulations. The simulations incorporate the most recent data on tropical land use change, regional differences in biomass and soil carbon density, and the conversion of forest to both shifting cultivation and to permanent agriculture. Carbon accumulation in fallow and immature forests and in organic soil wetlands also is included. The study represents the first attempt to integrate all these factors into an estimate of the tropical forest carbon balance.

Model simulations indicate that releases of 0.30 to 0.48 Gt/yr occur in South America, the region with the largest forest area, although its deforestation rates are lower than the global average. In Southeast Asia, where mean regional forest biomass is high, carbon release rates range from 0.17 to 0.34 Gt/yr. Our simulated releases are significantly lower than those resulting from some earlier analyses which evaluated less detailed data on land-use change and carbon densities. The results, which agree with other recent papers, suggest that tropical forests, when compared to fossil-fuel sources, are presently a relatively small carbon source. However, an understanding of the biosphere's role in the global carbon cycle requires further refinement in analysis of the many asynchronous regional carbon pools.

1. INTRODUCTION

The increasing carbon dioxide (CO_2) concentration in the atmosphere has sparked concern that global warming and climatic change might occur in the near future (National Academy of Sciences 1983, Seidel and Keyes 1983). Atmospheric CO_2 has increased from preindustrial concentrations of 250-290 ppmv (parts per million by volume) to 340 ppmv in 1980 (Keeling and Bacastow 1977). The main source of atmospheric CO_2 is combustion of coal, oil, and gas which released approximately 5 Gt (1 Gt = 10^9 t) in 1980 (Marland and Rotty 1983). Although the oceans form a sink for atmospheric carbon, taking up approximately 2 Gt/yr (Broecker et al. 1979), whether the biosphere is a net source or sink remains a major unanswered question in carbon cycle research (Clark et al. 1982). The present paper focuses on quantifying the role of the biosphere, particularly the tropics, within the global carbon cycle.

The role of the biosphere and the degree of its influence on the carbon cycle is largely determined by the extent of human disturbance of natural ecosystems. Most undisturbed ecosystems are assumed to be in equilibrium with respect to carbon exchange. However, after disturbance, carbon stored in the biota and soils is released to the atmosphere. The balance between the carbon release from disturbed ecosystems and carbon storage in regrowing vegetation largely determines if the biosphere is functioning as a net sink or source of atmospheric CO_2. Analysis of the role of the biosphere in the global carbon cycle continues to focus on estimation of the carbon exchange of forests, emphasizing deforestation rates and carbon storage in biomass and soils.

Tropical forests are the single largest carbon pool in the terrestrial biosphere, storing over 50% of the 860 Gt found in biomass and soils of the world (Olson et al. 1983). Although recent clearing of tropical forests has been suggested as a source of atmospheric CO_2 second only to fossil-fuel (Bolin 1977, Hampicke 1979, Woodwell et al. 1978), estimates of the source strength have varied widely among workers using different models and data. Houghton et al. (1983) estimated carbon release to range from 1.8–4.7 Gt/yr for the entire biosphere (about 80% in the tropics), whereas Detwiler et al. (1984) estimated tropical releases to be 0.5–1.9 Gt/yr. Estimates by Detwiler et al. (1984) may be too low because they have not yet incorporated soil carbon releases, while estimates by Houghton et al. (1983) appear to be too high because they used biomass values and clearing rates which the latest evidence suggests are overestimates. Furthermore, both studies have relied on biomass estimation for the whole tropics without developing region-specific estimates.

The purpose of this paper is to describe results from current tropical carbon exchange modeling, which incorporates several improvements in the tropical forest data base. As described below, our projections of carbon exchange in 1985 (a) utilize the latest data on tropical land-use change; (b) distinguish clearing from permanent agriculture and shifting cultivation; (c) test how mean regional biomass values affect carbon release; (d) disaggregate biomass data into 10 tropical regions and 4-6 vegetation types; (e) include soil carbon dynamics in disturbed forests and in recovering vegetation; and (f) model the carbon exchange of organic soil wetlands, a subregional carbon pool previously regarded as insignificant in the overall carbon balance. Similar runs made at Cornell University agree generally with the Holcomb runs presented here.

2. PATTERNS OF LAND-USE CHANGE

Rate of land-use change appears to be the single most important factor determining the magnitude of carbon release, if other parameters such as biomass or carbon oxidation rates are held within a credible range (Woodwell et al. 1983). Several studies have relied on indirect estimates of deforestation based on population growth and wood production rates (Revelle and Monk 1977, Houghton et al. 1983) in the absence of more direct estimates of clearing. Similarly, some earlier surveys which considered only a subset of forest types and disturbance (Myers 1980, Persson 1974) were extrapolated to all forest types to determine how different cutting rates influenced carbon releases from the tropics (Houghton et al. 1983). The latest available assessment of tropical land-use change by FAO/UNEP (1981a,b,c), however, is relatively complete (76 countries considered) and distinguishes between different land uses and forest-cover types. Therefore, these data were used as the basis of our simulation runs of carbon exchange in tropical forest areas subjected to clearing for agriculture.

The FAO/UNEP inventory considers only land-use patterns observed in the 1976–1980 period. Rates of land-use change in 1985 were based on differences between forest area projected by FAO/UNEP for 1985 and land use statistics for

1980 (Table 1, Fig. 1). For all analyses, individual-country data were aggregated into ten regions (Armentano et al. 1984): two in Asia, five in Africa, and three in Latin America and the Caribbean.

Forest inventory data from FAO/UNEP (1981a,b,c) were aggregated into four major land-use categories: primary vegetation, logged vegetation, shifting cultivation/fallow, and bush. A fifth category, permanent agriculture and human settlement, was calculated for each region by subtracting other categories from the total land area. Our classification scheme for both coniferous and broad-leafed forests followed Lanly (1982), who considered any closed forests undisturbed for at least 60 to 80 years to be primary forest. Logged forests were defined as those recorded within the last 60 to 80 years plus forests heavily harvested annually. Areas of shifting cultivation/fallow were taken from FAO/UNEP estimates of fallow. Woody-vegetation formations that could not be classified as closed forests, including open-woodland savannas and bamboo and shrub areas, were combined as bush.

TABLE 1. SYMBOLS, DEFINITIONS, DATA SOURCES, AND CALCULATIONS FOR TROPICAL LAND-USE CHANGE (*see* Fig. 1)

Our Symbols	Definitions	FAO Classes	FAO/UNEP (1981a,b,c) Source for 1980, 1985 data
PV	Primary Vegetation	NHC/NSfluv, NHC/NSf2	Tables 1a, b; 7a, b
LV	Logged Vegetation	NHC/NSfluc, NHC/NSf1m	Tables 1a, b; 7a, b
SW	Shifting Cultivation	NHC/NSa	Tables 1a, b; 7a, b
BU	Bush	NHB, NHBa, NHc/NHO, NHc/NHOa, nH	Tables 1c, e, f; 7c, e, f
AG	Agriculture	-----	Formula 2 (below)
Fluxes			Calculations
ΔPV	Loss of PV		Formula 1 (below)
PV_{DEF}	Deforestation of PV		Tables 6a,b
LV_{DEF}	Deforestation of LV		Tables 6a,b
$PV \rightarrow LV$	Logging of PV		$\Delta PV - PV_{DEF}$
TDR	Total Deforestation Rate		$PV_{DEF} \bullet LV_{DEF}$
ΔSW	Change in Swidden Area		Formula 1
ΔBU	Change in Bush Area		Formula 1
ΔAG	Change in Agricultural Area		Formula 1

Formulas

1. $\Delta PV = \dfrac{\text{1985 value} - \text{1980 value}}{5}$

2. $AG = \text{Total Land Area}^{*} - (PV+LV+SW+BU)$

*FAO (1978)

The land-use classification is particularly useful for distinguishing shifting cultivation from permanent agriculture. Some previous studies have considered only one category of agriculture (Houghton et al. 1983), assuming that all clearing for food production results in permanent or long-term loss of natural vegetation (Woodwell et al. 1978, Houghton et al. 1983). Detwiler et al. (1983; in press) pointed out the importance of shifting cultivation for realistically estimating tropical carbon dynamics. Large areas of tropical land are actually cultivated for only 2-3 years after clearing (FAO 1981a,b,c). Abandonment leads to accumulation of carbon in the fallow stage, while under permanent agriculture, carbon stores remain low.

Before simulating carbon exchange, FAO woody vegetation data were converted into region-specific ecosystem areas. Table 1 and Figure 1 detail the logic for calculating land transfers and show how FAO/UNEP data were used to calculate land-use change rates (for a more complete description see Armentano et al. 1984). Table 2 contains a summary of land-use conversion rates for the major tropical regions. Hall et al. (personal communication) have done a similar analysis but did not aggregate the national data by region.

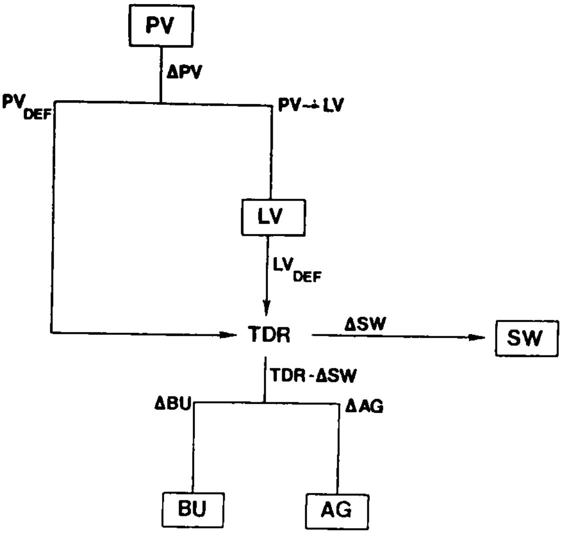

Figure 1. Methodological logic of computing vegetation alterations used in simulations of tropical upland ecosystem land-use change. Data obtained from FAO/UNEP (1981a,b,c). For detail on symbols, *see* Table 1.

TABLE 2. 1985 LAND-USE CONVERSION RATES IN FIVE TROPICAL REGIONS
Calculated from FAO (1978) and FAO/UNEP (1981a,b,c)

Conversion	Southeast Asia	South Asia	Africa	South America	Central America and the Caribbean	Totals
Primary Forest to Logged Forest	1,415	23	474	1,771	211	3,894
Logged Forest to Shifting Cultivation	480	135	795	519	132	2,061
Primary Forest to Shifting Cultivation	188	78	216	607	280	1,369
Logged Forest to Permanent Agriculture	603	10	239	999	199	2,050
Primary Forest to Permanent Agriculture	239	6	76	1,168	414	1,903
Bush to Permanent Agriculture	170	0	976	1,540	13	2,699
Fallow to Shifting Cultivation	5,791	1,029	6,165	7,764	3,098	23,847
Primary and Logged Forest to Bush	0	74	2	0	0	76

3. CARBON DENSITIES AND DYNAMICS

To estimate carbon exchange in tropical regions, information is required on carbon densities (in tC/ha) of biomass and soils of each ecosystem type, rates of land use change, and the fate of cleared vegetation (Hall et al. in press; Detwiler et al. in press). With these data, the dynamics of carbon exchange in undisturbed, disturbed, and recovering systems can be calculated. Because tropical ecosystems differ regionally in mean carbon density (Brown and Lugo 1984), carbon density should be defined separately for each region to the extent that available data allows. The regional distinctions prevent misconceptions as to carbon release from specific regions and facilitate evaluation of sources of error and uncertainty in global carbon analyses.

3.1 Predisturbance Forest Biomass

Tropical forests on mineral soils occupy most of the tropics and therefore are of primary interest in estimating carbon releases. In general, biomass increases with temperature and moisture. Thus, values are highest for rain forests and wet forests (Brown and Lugo 1980). Greatest biomass is found in Southeast Asia lowland rainforests, often dominated by commercially prized dipterocarps (family Dipterocarpaceae) (Myers 1980). Destructive sampling of productive sites has shown that biomass in old-growth dipterocarp stands can exceed 500 tC/ha (Brunig 1977). Over large areas encompassing site variability, however, mean values for Southeast Asian rain forests are no more than 200 tC/ha (Cannell 1982, Chan and Olson 1983).

Forest biomass variability is caused both by site and climatic factors and by degradation associated with past disturbance. Thus tropical forests in Africa and Latin America average about 50 to 85% of the biomass of Southeast Asian forests (Table 3). In parts of Latin America, the lower biomass may result from past disturbance of sites that have recovered enough to be classified as primary forest. In areas such as the Amazon Basin, productivity is often limited by low soil-nutrient availability (Sanchez et al. 1982).

TABLE 3. ESTIMATED ABOVE-GROUND BIOMASS AND SOIL CARBON CONTENT (tC/ha) FOR TROPICAL FOREST REGIONS IN MODEL RUNS. THE VALUES ARE MEANS WEIGHTED FOR THE AREA OF VARIOUS FOREST TYPES

Region	Undisturbed Sites	All Sites Olson et al. (1983) Low	All Sites Olson et al. (1983) High	Soil Carbon[b]
Southeast Asia	252	108	178	132
South Asia	107	75	126	65
East Africa	122	60	103	67
West Africa	123	63	106	70
Central Africa	139	76	127	66
North Africa	103	47	79	51
South America	129	85	143	72
Central America	117	66	137	62
Caribbean	132	90	151	79

[a] Literature Sources: Cannell (1982), Snedaker (1980), Brown and Lugo (1980), Chan and Olson (1983), Grubb (1977), Brunig (1977), Anderson et al. (1983). See Armentano et al. (1984) for details on aggregation of biomass data.

[b] Literature Sources: Brown and Lugo (1980), Yoda and Kira (1969), Chan (1982), Schlesinger (1979) and Edwards and Grubb (1977).

Because biomass estimates varied widely, we tested the sensitivity of carbon exchange estimates to a range of biomass values. One set of simulations was based on a compilation of biomass studies of forest sites having no apparent prior disturbance (Table 3). However, since these data were not available for all regions and ecosystems, estimates from Brown and Lugo (1980) were substituted where gaps occurred. As an alternative, the extensive survey of Olson et al. (1983) of the literature on ecosystem biomass values provided mean values for large areas which include forests subjected to varying degrees of disturbance (Table 3). For both cases, below-ground biomass was estimated from above-ground values by multiplying by a factor of 16 to 25%, depending on the literature data (Cannell 1982).

Presentation of biomass values as a range of high and low values reflects natural variability and the uncertainty implicit in a limited data base, and incorporates some studies of productive sites (Olson et al. 1983). However, studies of individual forests in Southeast Asia and Africa report biomass values considerably in excess of the Olson et al.'s (1983) maximum mean biomass values. In contrast, specific studies in the three neotropical regions focused on forests that were intermediate in biomass accumulation between Olson et al.'s range of region-wide biomass estimates.

The organic matter content of soil also varies by ecosystem and region (Table 3). Carbon content generally increases with increasing precipitation and decreasing temperature (Zinke et al. 1983), and varies regionally. Soil carbon content is greatest in mangrove and swamp ecosystems where water tables are near or above the soil surface for long periods (Chan 1982). Organic wetland soils have the highest carbon content, storing up to ten times more carbon per hectare than upland soils (Armentano et al. 1984).

3.2 Disturbance of Ecosystems

Disturbance of ecosystems ordinarily reduces biomass and soil carbon content, with the type of disturbance determining the magnitude of loss. Greatest carbon loss takes place when forests are converted to permanent agriculture and human settlements. Agricultural ecosystems, which are the commonest result of forest clearing, have biomass values that average from 5-16 tC/ha, depending on the crop (Olson et al. 1983). Agriculture thus retains only 5-10% of predisturbance carbon densities. Most of the forest biomass is oxidized, principally as exponentially decaying detritus or necromass. An additional fraction of the biomass carbon, estimated at 25%, is instantly oxidized by fire (Seiler and Crutzen 1980). A third component, refractory charcoal, remains as unoxidized carbon for centuries. Decay of necromass was calculated based on decay rates of foliar and wood components (Furtado et al. 1980, Nye and Greenland 1960, Swift et al. 1980, Chan and Olson 1983), weighted by the contribution of each component to necromass (Armentano et al. 1984).

Tropical agriculture consists of both shifting and permanent cropping systems. Where shifting agriculture is practiced, land is cleared and cultivated for a few years and then abandoned. Abandonment leads to revegetation of the site, a process which results in increased carbon in the vegetation and soils. Based on the few studies available, biomass in most secondary forests recovers to about 60% of predisturbance biomass; however, if left undisturbed, the recovering biomass eventually would approach predisturbance values, where the site is not degraded. Biomass recovery begins in the same year as abandonment.

In contrast, soils continue to lose carbon after abandonment. Soil carbon levels in recently cleared forests drop steadily for approximately 15 years after disturbance. A new equilibrium carbon content is then approached, estimated to equal about 60% of the original forest soil content (Seubert et al. 1977, Nye and Greenland 1960). Oxidation of organic matter in shifting cultivation releases on average about 25% of the forest soil carbon (Nye and Greenland 1960).

3.3 Organic Soil Wetlands

Lowland swamp regions with organic soils are of interest because of their high soil-carbon content and because of reported recent disturbance, especially in Southeast Asia (Armentano et al. 1983, Chan 1982). Although these systems occupy relatively small areas of the tropics, they store more soil carbon per hectare than ecosystems on mineral soils. Because FAO inventories did not treat organic soil wetlands separately, data from other sources were used to analyze the role of organic soil ecosystems in tropical carbon exchange (Armentano et al. 1983, Armentano et al. 1984). Tropical organic soils have been developed primarily in Southeast Asia and to a lesser extent in eastern Africa (Table 4).

TABLE 4. AREAS OF TROPICAL WETLAND CONVERSION TO AGRICULTURE

Country	Total Area Converted (10^3 ha)	Time	References
Indonesia	1119	1950–1980	Armentano et al. (1984)
West Malaysia	407	1930–1980	Armentano et al. (1984)
Sierra Leone	7	1976–1980	FAO/UNEP (1981a)
Liberia	40	1976–1980	FAO/UNEP (1981a)
Uganda/East Africa	104	1935–1980	Jameson (1970)
Rwanda	1.5	1970–1980	Arid Land Information Center (1981b)
Ivory Coast	3	1970–1980	Lassoudiere (1976)
Jamaica	1.2	1980–present	Kennard (1982)

Development of wetlands for agriculture usually requires lowering the water table by use of drainage canals. The resulting oxidation of the soil organic matter can release large amounts of CO_2 to the atmosphere, depending on cropping practices and peat depth. For example, peat oxidation rates in Malaysian peat soils drained for agriculture were estimated to range up to 64 tC/ha/yr from data of Coulter (1957). In contrast, oxidation rates in peat soils drained for rice were estimated to be 17 tC/ha/yr, based on the duration of flooding for a single rice crop (Armentano et al. 1984). In the absence of drainage, however, organic soils function as carbon sinks (Anderson 1964). An estimate of 0.8 tC/ha has been calculated as a typical rate for carbon sequestering in undisturbed peatlands in Southeast Asia (Armentano et al. 1984). Thus, drainage causes a shift in the role of organic soils in the carbon cycle (Armentano et al. 1983, 1984). Because of the nature of wetland carbon exchange, developed wetland areas will still be releasing carbon years after development. Thus, in estimating carbon for a specific year, the history of drainage for prior decades and the time-trend of carbon release must be simulated. In most other ecosystem types, release of carbon from disturbances prior to the past several years before disturbance is very small.

4. MODELING OF CARBON DYNAMICS

Rates of carbon exchange in the tropics were computed with the simulation model, GLOBC7, developed at Cornell University (Detwiler and Hall 1980, Detwiler et al. 1981, Hall et al., in press, Bogdonoff et al., in press). The model calculates changes in carbon storages and releases from ecosystems following conversions of land of known area to terrestrial land-use categories. The release of carbon to the atmosphere and long-term storage of carbon as charcoal or wood products is also calculated (Figure 2). For each land-use category, carbon density is specified for three compartments: above and below ground biomass and soil carbon.

Five model compartments correspond to the five land-use categories previously described: primary vegetation, logged vegetation, shifting cultivation/fallow, bush, and permanent agriculture. Cycles of disturbance and establishment of equilibrium carbon densities in recovering systems can be simulated (Figure 2). Undisturbed organic soil wetlands and abandoned agricultural land, both of which accumulate soil carbon, are treated as special cases of these cycles.

Carbon fates for each transfer are specified according to specific land-use conversions. For example, forested land cleared by shifting cultivators is farmed for 2–3 years before the land is abandoned. Vegetation recovery and accompanying biomass storage begin immediately following cultivation, and soil continues to lose carbon for several years after such regrowth. GLOBC7 calculates separately the rates of carbon exchange of biomass and soils. The

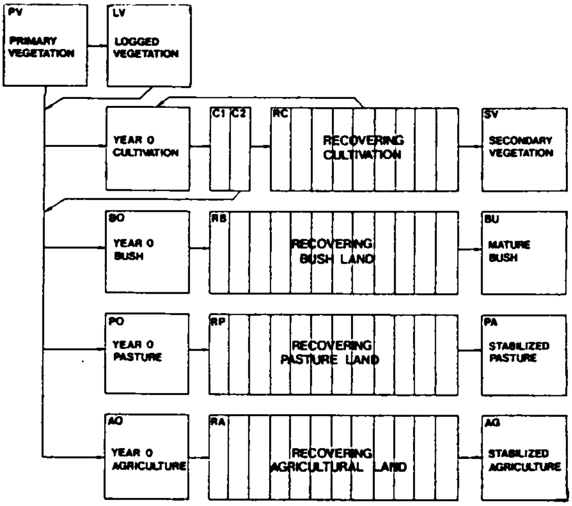

Figure 2. Land-use classification and transfer of tropical ecosystems in GLOBC7 model. (From Bogdonoff et al., in press.) Wetland runs use "recovering cultivation" to simulate natural accretion of carbon in undisturbed organic soils.

simulations used data summarized in Tables 2–4. Literature data are described in more detail in Armentano et al. (1984). If no specific regional data were available, worldwide averages or values from similar regions were used. Upland simulations were run for 1980–1985. Thus carbon exchange rates reported for 1985 include estimates of CO_2 release from decay of necromass produced from clearing in the past five years. For wetlands, the historical pattern of carbon exchange from 1900 until the present was simulated.

5. SIMULATION RESULTS

The land-use changes projected for 1985 in the tropics will release 0.60–1.02 Gt/yr C for the period 1980–1985 (Table 5). (These projections utilize the area-weighted carbon density data of Olson et al. [1983].) If biomass data from studies of undisturbed sites are substituted after calculating regional carbon densities based on ecosystem areas, a carbon release rate of 1.08 Gt/yr is obtained. Thus, the difference between simulated releases based on Olson et al.'s high biomass values and biomass values from exceptionally old-growth sites is only 0.06 Gt. These results suggest that because, over large areas, most tropical forests contain less carbon than the exceptional sites, carbon release rates fall below 1 Gt/yr.

Regardless of the biomass data used in simulations, Southeast Asia and South America are the regions of greatest carbon release (Table 5). In South America, carbon release ranges from 0.30–0.40 Gt/yr, 44-48% of the total for the tropics, even though biomass carbon densities there are only moderate. Annual deforestation rates equal 0.6% of the extant forest area, an annual loss of 2.7 million ha of primary forest. With a projected 5% annual deforestation increase (FAO/UNEP 1981c), and large unexploited areas still available, carbon release from South America will probably continue to increase into the near future.

Carbon releases from Southeast Asia range from 0.17–0.34 Gt/yr, a higher release on a unit area basis than elsewhere, because biomass and soil carbon content is relatively high (Table 3). Deforestation is occurring at 0.7% annually, half of this resulting from shifting cultivation. Although 65% of Southeast Asia is still forested (FAO 1981b), selective logging has disturbed a large portion of this area, releasing carbon in the process. Forests in other tropical regions such as South Asia and Central America are less extensive and already heavily disturbed.

TABLE 5. CO_2 RELEASE BY REGIONS

Region	Range for Current Annual Release (Gt)
Southeast Asia	0.170 – 0.337
South Asia	0.015 – 0.022
East Africa	0.038 – 0.048
Central Africa	0.021 – 0.040
North Africa	0.004 – 0.004
West Africa	0.023 – 0.042
South America	0.302 – 0.480
Central America and Caribbean	0.059 – 0.110
TOTAL	0.633 – 1.083

Despite Africa's large area, carbon releases ranged from 0.086–0.134 Gt/yr, only 12–14% of the tropical total. The chief areas of forest loss are located in semiarid and subhumid climates where forest carbon stocks are relatively low (FAO/UNEP 1981a, Brown and Lugo 1980). Over half of African moist tropical forests are located in Zaire, a lightly populated country with little forest disturbance (Library of Congress 1980).

Annual carbon release from tropical organic soils equaled 0.015 Gt in 1980 (Table 6). Although tropical organic soils contributed only a small percentage to the total tropical exchange, their exploitation also represented a loss of net carbon-sequestering capacity which functioned in the predisturbance era at a rate of 0.034 Gt carbon per year. Thus, the total annual shift in carbon exchange due to tropical wetland disturbance is presently at least 0.05 Gt. Almost the entire shift has occurred since 1950, with Southeast Asian wetlands most significant. The wetland carbon shift in Southeast Asia comprises 17–25% of the total regional release. In East Africa, the apparent carbon shift in wetlands is 13–17% of the estimated regional release.

TABLE 6. CARBON EXCHANGE OF TROPICAL ORGANIC SOILS BY COUNTRY (from Armentano et al. 1984)

Country	Organic Soil Area in 10^6 ha	ANNUAL EXCHANGE (10^6 TC)[b]	
		Predisturbance	1980
Indonesia	20.0	-16.27	16.80
West Malaysia[a]	1.20	- 0.89	8.96
Ivory Coast	0.15	0.0	0.12
Sierra Leone/Liberia	1.0	0.0	2.59
Jamaica	0.01	- 0.010	0.036
Rwanda and Uganda	0.66	- 0.59	3.16
Other	20.5	-16.44	-16.44
TOTAL		-34.20	+15.22

[a] Includes Sabah and Brunei; Sarawak is included in the "other" category.

[b] Negative numbers indicate a sink.

6. DISCUSSION AND CONCLUSIONS

Simulations of the carbon exchange of the world's tropical regions, using the most recent land conversion and carbon density data, indicate that net carbon release falls within the range of 0.6–1.1 Gt/yr. These results are significantly lower than estimates reported five years ago (Woodwell et al. 1978), but are consistent with results of Detwiler et al. (1984) (Table 7). At the regional level, our estimate of carbon release 0.17–0.34 Gt/yr for Southeast Asia agrees with the 0.32 Gt/yr net release estimated by Chan and Olson (1983).

Although biomass and soil carbon values are modeled differently by various investigators (Table 7), differences in simulations are probably not due to algorithm differences; our model results resemble Houghton et al.'s (1983) when similar data and assumptions are used (Woodwell et al. 1983). Thus, data differences are more important than model structure. Earlier work had estimated tropical carbon releases of 1–7 Gt/yr or more based on clearing rates of 1%/yr (Woodwell et al. 1978). However, latest FAO assessments (Lanly 1982) indicate that only 0.6% of all closed, broad-leaved forests are being cleared annually. More important, clearing of undisturbed productive broad-leaved forests, the ecosystem type with highest carbon density, is estimated to be only 0.27%/yr, whereas logged-over lower-biomass secondary forests are being cleared at 2.06%/yr. Thus the mean biomass of forests being cleared shifts downward when disturbance and site potential are considered. In addition, the differentiation of shifting cultivation/fallow from permanent clearing also lowers predicted carbon release. Therefore, reliable data on the vegetation type subject to disturbance, and the kind of disturbance, emerge as critical needs for terrestrial carbon modeling.

TABLE 7. ESTIMATES OF CARBON RELEASES FROM THE TROPICS, AND FACTORS INCLUDED IN THE ESTIMATES

Author	Clearing Rates	Biomass	Soil	Shifting Agriculture	Carbon Release (Gt)
Woodwell et al. (1978)	High	High	Yes	No	1.0–7.0
Olson (1982)	NA[a]	Low-High	Yes	Yes	1.3-2.5
Houghton et al. (1983)	Low-High	High	Yes	No	1.8–4.7[b]
Detwiler et al. (1984)	Low-Medium	Low-High	Yes	Yes	0.7–2.2
This Paper	Medium	Low-High	Yes	Yes	0.6–1.1

[a] not available

[b] world-wide release, tropics comprise 80% or more of total

Testing a range of forest carbon densities shows that this parameter is only secondarily important in explaining differences in carbon release estimates. The use of 200 tC/ha of total biomass for moist forests and 160 tC/ha for seasonal forests by Houghton et al. (1983) overestimates biomass for all regions except Southeast Asia. However, from our model runs, it appears that biomass accounts for differences in carbon release estimates only on the order of 0.50 Gt/yr.

Because secondary forests are most often cleared, the use of the biomass data from only productive, undisturbed sites is not warranted. Realistic biomass values probably are closer to the middle or low end of Olson et al.'s (1983) estimates. This generalization may not be valid for Southeast Asia, where high biomass virgin dipterocarp forests are currently being cleared. Closed productive forests, which are probably best estimated by Olson et al.'s (1983) high values, are being cleared for agriculture at a relatively low rate. Thus total carbon release may be no more than 0.8-0.9 Gt/yr. New volume inventories for tropical countries (FAO/UNEP 1981a,b,c) add strength to this conclusion because they suggest even lower mean biomass (Brown and Lugo

1984) than used in our simulation. An additional factor to consider is carbon loss in converted forest soils. Schlesinger (1983) reports that the available literature indicates that 79% is the best estimate of the proportion of forest soil carbon retained in agricultural soils. Hence, carbon modelers may have overestimated the loss rate, thus overestimating carbon releases.

The tendency for improvements in the data base to produce lower estimates of tropical carbon release raises important questions about the biosphere's role in the overall carbon budget. First, it is apparent that future refinements of carbon release estimates will result in changes on the order of 0.1 to 0.2 Gt/yr rather than 1 Gt/yr or more as in the past. At this level of release, subregional or relatively local ecosystem types become important considerations in making reliable global estimates. Thus, for example, a shift in carbon balance in tropical organic soil wetlands of 0.05 Gt/yr can no longer can be dismissed as insignificant in the balance of regional carbon releases. Since future development in the tropics is likely to focus on wetlands as population size and demand for arable land expands, future CO_2 releases from tropical wetlands may become an increasingly important component of tropical carbon exchange.

Second, temperate-zone carbon dynamics will become recognized for their importance in the carbon release of the entire biosphere. Although once considered secondary to the tropics in the global carbon balance (Woodwell et al. 1978), current temperate zone carbon dynamics may be of major significance. Since estimates of temperate zone carbon exchange vary from a small source (Houghton et al. 1983) to a net sink of 1.0–1.9 Gt/yr (Armentano and Ralston 1980, Johnson and Sharpe 1983), temperate zone carbon storage could more than balance tropical releases. Therefore, improvement in temperate carbon balance estimates is needed to determine the dynamics of simultaneous sources and sinks throughout the biosphere. Only after the net balance of the many asynchronous regional carbon pools is understood will the carbon balance of the biosphere and its role in the global carbon cycle be known.

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