Tropical Deforestation: Some Effects on Atmospheric Chemistry

Report

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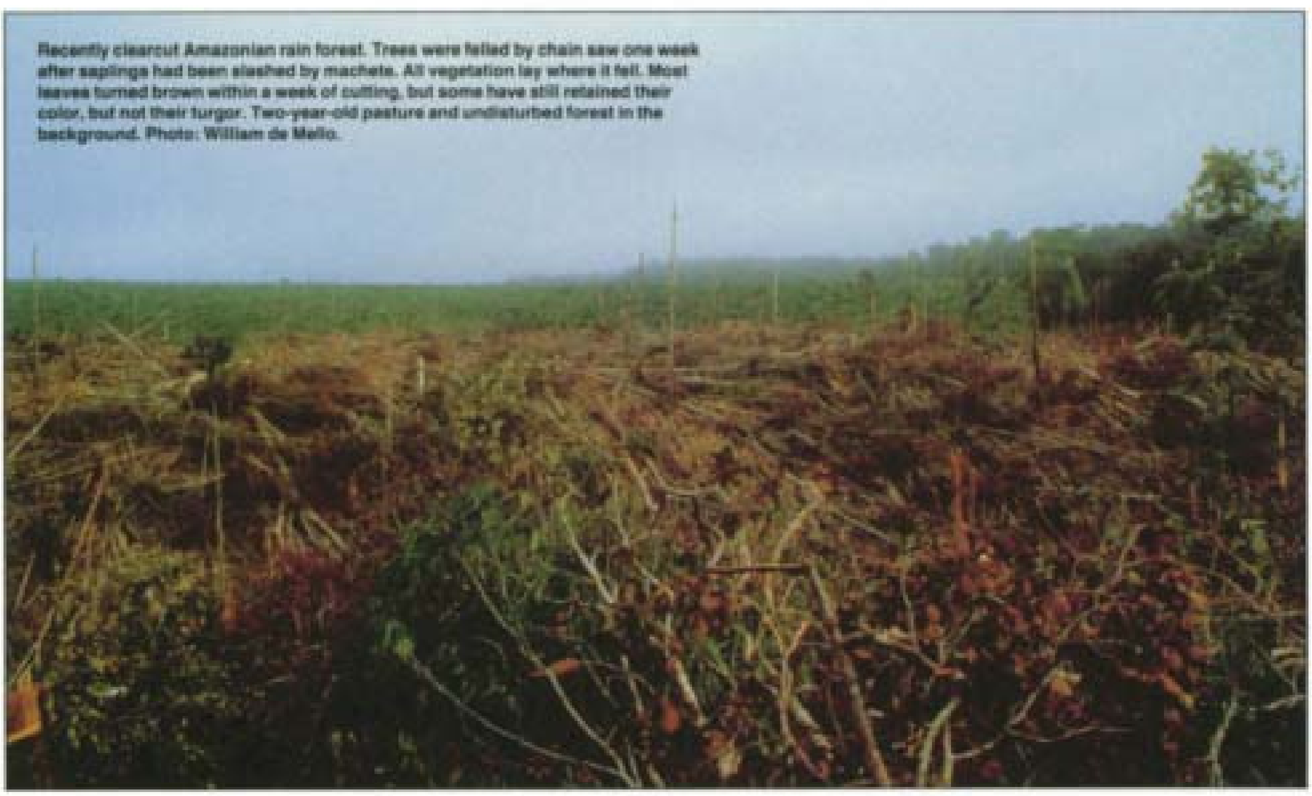
Measurements of carbon dioxide, nitrous oxide, and methane released from Amazonian soils show that tropical deforestation acts on a variety of time scales to exacerbate the atmospheric greenhouse problem. The global importance of tropical forest soils in the atmospheric carbon cycle and its susceptibility to alteration by human land-management practices implies that the solution to the human-induced climate change problem lies in a combination of combustion source controls, conservation of existing tropical rain forests, and large-scale upgrading of productivity on currently degraded tropical soils.

INTRODUCTION

The concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), three atmospheric gases which are major regulators of global temperature and the ozone layer, are steadily increasing in the atmosphere (1, 2). Fossil-fuel combustion and biomass burning are important and increasing sources of these gases, and predictions of future global climate change have been largely based on extrapolation of fossil-fuel combustion rates. However, these gases originate mainly from natural biological processes, which are especially intense in the tropics (3, 4). The amount of carbon dioxide released by fossil-fuel combustion is now about $5.2 \cdot 10^9$ tons $C \cdot yr^{-1}$, but the amount released from soils is roughly ten times greater, at $53 \cdot 10^9$ tons $C \cdot yr^{-1}$ (5). Gross terrestrial primary production is estimated to be around $120 \cdot 10^9$ tons $C \cdot yr^{-1}$ (6). This figure is very uncertain and could be quite a lot higher if tropical gross productivity and respiration have been underestimated; as is likely because they are often estimated from net biomass productivity assuming temperate-plant respiration rates (7). Recent data on stable oxygen isotope composition of atmospheric carbon dioxide is also consistent with higher rates of global gross productivity and respiration than earlier estimates, with the discrepancy likely to lie in the tropics (8).

If global net primary production were to vary only a few percent, changes in atmospheric carbon dioxide, which are as large as global combustion sources, would result. During the El Niño year 1982, atmospheric carbon dioxide failed to rise in the atmosphere despite combustion inputs, but it subsequently rose at twice the previous normal rate in 1983 before settling down (1). Changes in oceanic sources and sinks of CO_2 are an unlikely cause since surface ocean warming in the East Pacific during El Niño would release the gas to the atmosphere and reduce nutrient upwelling, decreasing photosynthesis and calcification of phytoplankton and coastal reefs. The observed atmospheric changes are more likely due to increased tropical forest growth (9), linked to the El Niño episode by the unusually high rains which accompanied it in much of South America, and to elevated respiration during the succeeding drier year, 1983. This pattern is strongly suggested by the satellite vegetation index maps for those years (10).



Recently clearcut Amazonian rain forest. Trees were felled by chain saw one week after saplings had been slashed by machete. All vegetation lay where it fell. Most leaves turned brown within a week of cutting, but some have still retained their color, but not their turgor. Two-year-old pasture and undisturbed forest in the background. Photo: William de Mello.

Table 1. Mean fluxes of carbon dioxide, nitrous oxide and methane from 18 Central Amazonian habitats and their variances (14). *Nine methane flux measurements averaged together because of high variability caused by bubble transport.

	n	$CO_2 \cdot 10^{13}$	$N_2O \cdot 10^{10}$	$CH_4 \cdot 10^{10}$
			Molecules · cm^{-2} · sec^{-1}	
			Primary Forests	
1. Porto Alegre	20	17.17 ± 12.86	1.49 ± 1.43	−1.58 ± 4.86
2. Esteio	4	20.51 ± 11.00	0.97 ± .58	−5.75 ± 2.00
3. Ducke	12	28.56 ± 12.63	0.57 ± .30	−2.93 ± 1.49
4. Ducke sand	12	21.31 ± 6.58	0.21 ± .14	−8.03 ± 3.39
5. Campina sand	11	36.07 ± 12.84	0.38 ± .56	−6.82 ± 4.20
6. Ducke marsh	10	15.45 ± 7.48	2.47 ± 3.65	0.90 ± 1.46
			Secondary habitats	
7. Flooded campina*	9	3.88 ± 2.36	−0.25 ± .25	2360*
8. Clearcut (PA)	30	15.45 ± 7.10	0.58 ± .56	−5.02 ± 2.29
9. Regenerating (PA)	20	15.20 ± 3.53	0.81 ± .37	−3.3 ± 2.24
10. Disturbed	36	15.38 ± 2.96	1.45 ± 1.05	−2.67 ± 8.49
11. Silviculture, sand	4	12.57 ± 4.40	0.24 ± .31	−5.88 ± 1.35
12. Silviculture, sand	3	29.07 ± 4.99	0.36 ± .01	−6.54 ± .44
13. Grassland (PA)	14	24.32 ± 7.10	0.11 ± .18	−0.22 ± 2.33
14. Pasture (E)	9	20.82 ± 3.04	0.19 ± .41	1.13 ± 2.02
15. Cowpeas	4	15.77 ± 3.91	0.85 ± .37	−2.30 ± 1.09
16. Plus fertilizer	4	16.57 ± 1.62	0.14 ± .11	−1.61 ± .79
17. Plus crop residue	4	18.41 ± 5.74	2.14 ± 2.8	8.06 ± 14.69
18. Weeded, bare soil	4	6.21 ± .99	0.72 ± .33	−1.92 ± .50

Ranch sites: PA = Porto Alegre
E = Esteio
n = number of measurements

Table 2. Classification of habitats studied in terms of land-use practices.

TYPE OF ALTERATION	HABITAT NAME	SITE
NONE	UNDISTURBED FOREST	1–6
PERMANENT FLOODING	DROWNED FOREST	7
SELECTIVE LOGGING	DEGRADED FOREST	10
CLEARCUT	REGENERATING CLEARCUT	8–9
BURNING		
SEEDING → TREES	SILVICULTURE FOREST	11–12
→ GRASS	GRASSLAND	13
CATTLE	PASTURE	14
LOGS CLEARED, SOIL PLOUGHED		
COWPEAS	AGRICULTURE 1	15
+ FERTILIZER	AGRICULTURE 2	16
+ CROP RESIDUES	AGRICULTURE 3	17
WEEDED	BARE SOIL	18

For key to site numbers see Table 1.

Table 3. Classification of habitats studied in terms of their mean fluxes between soil and atmosphere.

CATEGORY	CARBON DIOXIDE	NITROUS OXIDE	METHANE
Very High	–	6 17	(7)
High	1 2 3 4 5 12 13 14	1 10	17
Medium	6 8 9 10 11 15 16 17	2 3 8 9 15	6 13 14
Low	18	4 5 11 12 13 14 16 18	1 2 3 4 5 8 9 10 11 12 15 16 18
Very Low	(7)	(7)	–

(For key to site numbers see Table 1.)

CATEGORY	CARBON DIOXIDE $\times 10^{13}$	NITROUS OXIDE $\times 10^{10}$	METHANE $\times 10^{10}$
		FLUX molecules · cm^{-2} · sec^{-1}	
Very high	>40	>2	>20
High	20–40	1–2	5–20
Medium	10–20	0.5–1	0–5
Low	5–10	0–0.5	−10–0
Very low	0–5	<0	<−10

Land-management practices which alter metabolic carbon exchange between biosphere and atmosphere should also have an appreciable effect on the atmosphere.

The Amazon jungle accounts for about half the world's remaining tropical rain forest (11–13). To compare forested and deforested tropical habitats as sources of the climatically significant atmospheric gases carbon dioxide, nitrous oxide, and methane, the fluxes of these gases to the atmosphere from soils were measured directly in 18 habitats in Central Amazonia (14). They included undisturbed tropical rain forests and cleared agricultural pasture, and secondary forest sites. This paper classifies land-use practices at each site, and contrasts primary and secondary sites as sources of atmospheric trace gases.

MATERIALS AND METHODS

Measurements were made at sites near the center of the Amazon region, within 70 km of Manaus, Brazil, on "Terra firme" forest soils not subject to annual river flooding. Distinctive forest types are found on clay soil and on sandy soil (15, 16). Yellow clay "Terra firme" soils cover about 95 percent of Central Amazonia. Sandy upland "campina" areas, like seasonally inundated "varzea" and "igapo" soils, occupy only a small percentage of the region (17). Sites were located in protected forest reserves run by the Instituto Nacional de Pesquisas da Amazonia (INPA), in commercial cattle pastures and adjacent forest preserves of the World Wildlife Fund (WWF)/INPA project on the Biological Dynamics of Forest Fragments (18–20), and at agricultural sites of the Empressa Brasileira de Pesquisa Agropecuaria (EMBRAPA).

Fluxes of gases to the atmosphere were measured from short-term concentration changes in the head space of chambers placed over the soil. Gas chromatographic measurements were made at INPA in Manaus. Multiple replicates were used, to permit calculation of both mean fluxes and their variances in each habitat. Within-habitat variances observed were due to real microsite differences, and were several orders of magnitude greater than the precision of the measurement (14). Full details of methods and site descriptions are given in reference 14, and readers are referred to that paper for a more detailed discussion of ecology of the area and mechanisms of gaseous carbon and nitrogen cycling in Central Amazonian soils.

RESULTS AND DISCUSSION

Table 1 shows the means and variances of gas fluxes from 18 Central Amazonian habitats. Our measurements apply largely to fluxes from soils in a limited region during the dry season, and do not, therefore, represent annual averages. Large spatial variations were found along soil and elevation gradients as well as within habitat variation on temporal scales from days to more than months (14).

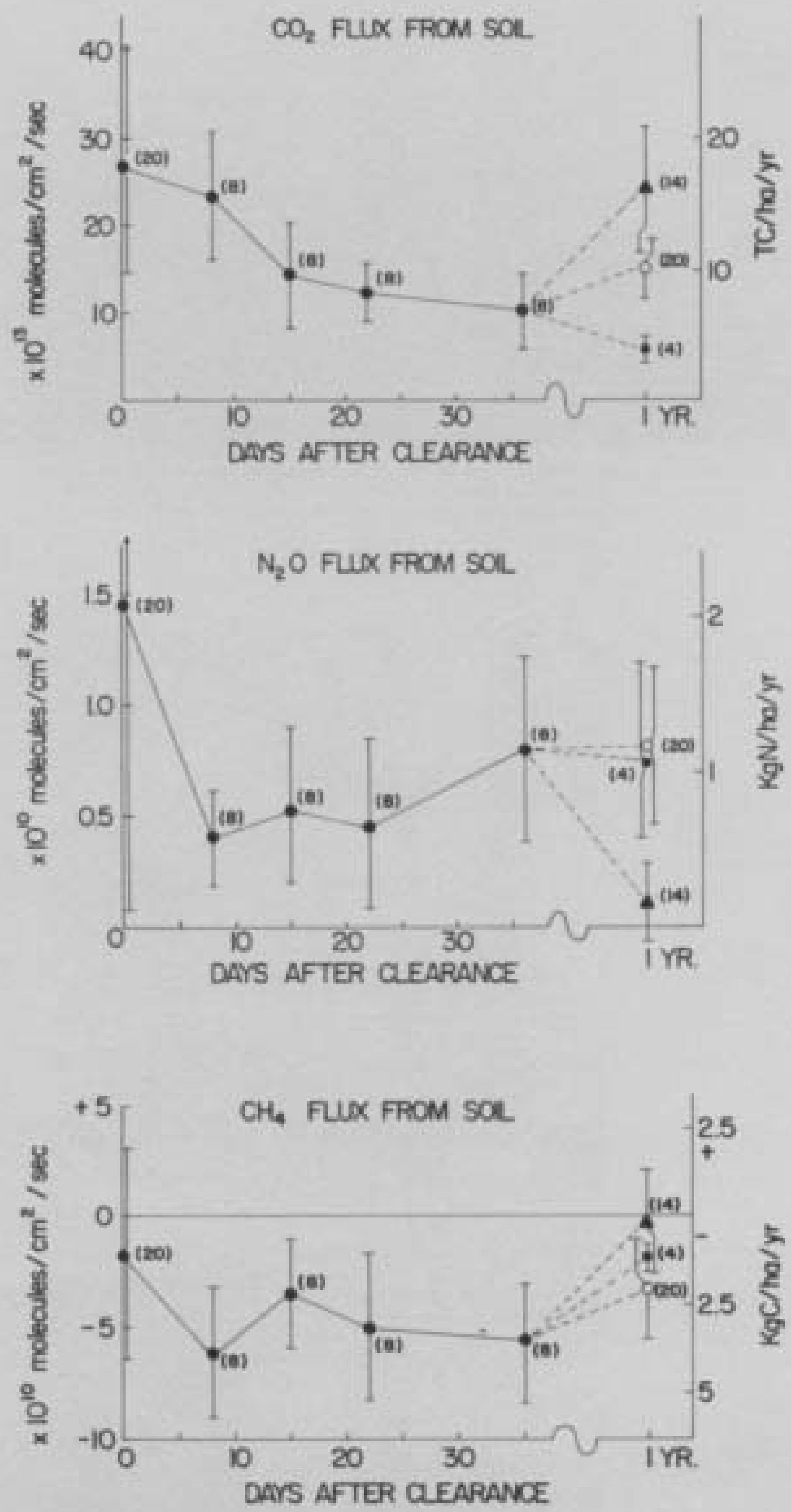
Habitats are classified with respect to land-use history in Table 2. Table 3 classifies the 18 habitats according to relative rates of release of each of the three gases.

Undisturbed Central Amazonian rainforest soils emit around $2.7 \cdot 10^{14}$ molecules $CO_2 \cdot cm^{-2} \cdot sec.^{-1}$, $1.13 \cdot 10^{10}$ molecules of N_2O, and $-2.5 \cdot 10^{10}$ molecules of CH_4 (14). Virtually identical fluxes were found in a Southeastern Brazilian coastal rain forest at Mangaratiba, R.J. (21). Measurements in coastal rain forest (latitude 23°S) were made during the warmest and wettest time of year, while the Amazonian forest measurements (latitude 2.5°S) were made during the dry season. If these measurements are representative of global tropical rain forests (area = $2.5 \cdot 10^{13}$ m^2), these data suggest that soils in this habitat provide some $1.6 \cdot 10^{11}$ CO_2, $5.2 \cdot 10^{6}$ N_2O, and $-5.5 \cdot 10^{6}$ CH_4 tons to the atmosphere per year (21).

Each gas showed a different pattern of change following clearcutting, depending on the type of land usage. Primary habitats released more carbon dioxide and consumed more methane than secondary habitats. Nitrous oxide had a more variable pattern: primary habitats on clay soils were large producers, but forests on sandy soils were not, and while pasture soils were minor sources of nitrous oxide some agricultural and secondary forest sites were substantial producers.

Changes in gas release from soil to atmosphere were followed for one month in freshly cut virgin rain forest. The forest was cleared for commercial cattle pasture, the major land use in the area, by standard methods: saplings were first chopped using machetes, followed one week later by felling of trees by chain saw. Vegetation lay drying out where it fell, in a dense tangle of trunks and boughs. This site was not burned. Mean flux values and their variances are shown in Figure 1. Values measured in undisturbed rain forest are shown at the left, and at the right values from a clearcut allowed to regenerate for one year without burning (open circle), a clearcut which was burned and planted to pasture-grass (*Brachiara decumbens*) (triangle), and a clearcut in which logs were removed and soil kept free of vegetation by weeding (square).

Figure 1. Fluxes of gas from soil to the atmosphere.
● Undisturbed rain forest.
■ Clearcut with logs removed and soil kept free from vegetation by weeding.
○ Clearcut allowed to regenerate for one year without burning.
▲ Clearcut that was burnt and planted to pasture grass *Brachiara decumbens*.
Figures in parentheses refer to references.



Boundary between grassland and primary rainforest, showing the tremendous contrast in standing biomass. The foreground, which slopes down to a creek, has been extensively colonized by weedy bushes. A bulldozed road by the forest edge shows the characteristic yellow color of the soil. Photo: William de Mello.

The forest floor in undisturbed Amazonian rainforest. Palms (equipped with thorns) dominate the understory. A one to two centimeter litter layer covers the yellow soil. In the foreground a flux chamber (27.5 cm diameter) is visible. Photo: William de Mello.

CARBON DIOXIDE AND DEFORESTATION

A marked two thirds decline in the rate of carbon dioxide release from soil to the atmosphere was seen within one month of clearcutting; apparently the result of declining root respiration after death of the living biota. Soil plots kept bare for one year released only about one fifth to one fourth as much CO_2 as rain forest. Year-old regenerating clearcuts released about half that of primary forest. Only soils of recently cleared pasture (1–2 years since burning) released carbon dioxide at rates comparable to primary forest. As neither biomass nor litter production in these grassland sites is comparable to primary forest (22), elevated rates of root respiration per unit biomass indicate very high respiratory losses of fixed carbon, even though the grasses have C-4 biosynthetic pathways, and should have very low rates of photorespiration compared to C-3 forest trees. This could partly be a consequence of elevated soil temperatures in those cleared sites (14). After a few years fields in this area are typically abandoned due to declining productivity (23–27). Such severely degraded sites were not examined in this study, yet secondary forest soils subjected to only mild disturbance (selective tree removal for charcoal production over 30 years previously) released about half as much carbon dioxide to the atmosphere as primary forest. Our results probably underestimate the net changes following deforestation, as most of the sites examined were more productive than they would be as little as one or two years later, due to exhaustion of the transient input of nutrients from burning (22).

NITROUS OXIDE AND DEFORESTATION

Nitrous oxide releases showed a marked drop to very low values within days of clearcutting, but mean releases doubled over the following month to levels less than half those of undisturbed forest, i.e. levels similar to those from bare soil and regenerating clearcuts. In contrast, pastures released very little nitrous oxide. Nitrous oxide fluxes from undisturbed rain-forest soils were very variable, with some sites consistently high and others low. Nitrous oxide release was very low from grassland and pasture on clay soils, and from undisturbed forests on sandy soils. Agricultural and older secondary forest had high N_2O release rates, comparable to primary forest on clay soils. These patterns appear to reflect plant-root distributions and competition for ammonium between nitrifying bacteria and soil mycorhizae (14). Little N_2O was released from cattle manure, perhaps because of insufficient dietary nitrogen.

METHANE AND DEFORESTATION

Only consumption of methane was seen in recent clearcuts and bare soil, but some sites in primary forest and in regenerating secondary forest released methane. Methane was intensely released from flooded forest and from termite nests. Low but

The soil surface in a one-year-old regenerating clearcut. Aboveground roots extend from a dead tree stump at top. All leafy litter has vanished, but twigs and branches remain on the soil surface. Passionflower vines sprawl over a soil surface which has turned grey, bleached, and is harder than the original yellow soil surface. Photo: William de Mello.

positive production of methane was noted from cattle manure in pastures, and where cowpea crop residues had been plowed under in an experimental agricultural field. Termite nests were very abundant in cleared fields because very little of the trunk biomass is burned, and with the exception of those species, whose wood is not tasty to termites, trunks are consumed by termites within a few years. Flooding of forest is common wherever road construction intersects streams, forming permanent lakes on the upstream side, drained by culverts which are often blocked. These lakes are permanent, and release very large amounts of methane. Amazonian deforestation therefore acts to exacerbate the global methane problem, ignoring the fact that the major use of deforested areas is pasture for ruminant, methane-producing cattle.

Amazonian forest soils are major regional sources of climatically active gases compared to aqueous habitats in the same region. Floodplain waters, which seasonally occupy around two percent of Central Amazonia, emit some 2–8 tons of carbon per hectare per year (14, 28), a much smaller amount of CO_2 per unit area than forest soils, and they consume small amounts of N_2O from the atmosphere (14, 28). Floodplain waters are intense sources of methane bubbles, releasing up to 1.6 tons of carbon per hectare per year (14, 29). This is a rapid rate, but it is only 0.032 tons $C \cdot ha^{-1} \cdot yr^{-1}$ averaged over the whole of Central Amazonia. This amount can be compared to that released by termite nests in unflooded "Terra firme" forest, about $7.8 \cdot 10^{-3}$ molecules of methane per molecule of carbon dioxide (14). This ratio is similar to that previously reported from African termites, supporting the view that termites are a globally significant source of methane (30, 31). Termites consume 40 percent of leaf litter fall (32) and most of the wood (33) in Amazonia (net primary productivity about $20\ T\ C \cdot ha^{-1} \cdot yr^{-1}$). If termites consume 50 to 75 percent of all litter they could produce about 0.08 to $0.12\ T\ C \cdot ha^{-1} \cdot yr^{-1}$ of methane, far more than local swampy sources. Wood-eating termite abundances decline in pastures as woody biomass is consumed (33), so that part of this contribution could first be stimulated and then decline within years.

TROPICAL FORESTS AND ATMOSPHERIC CARBON DIOXIDE

Soil sources of carbon dioxide can be classified into 1. respiration of living biomass (primarily from plant roots); and 2. breakdown of dead organic matter (primarily by soil bacteria, fungi, and insects). After clearcutting the first will be largely eliminated, but the second will be stimulated by the addition of fresh decomposable organic matter. The rapid decline in carbon dioxide release from soils after deforestation suggests that respiration of live roots, and of those insects, fungi and bacteria that depend directly on living vegetation for their food, make up roughly some three fourths of carbon dioxide production. Areas kept clear of vegetation for a year released only a small amount of carbon dioxide compared to vegetated habitats. This finding is in accord with the findings of Waksman in 1927 (34) that root respiration supplies the bulk of carbon dioxide emitted from soils. Carbon respired by plant roots is much more rapidly recycled to the atmosphere than carbon dioxide derived from breakdown of litter, wood, and soil humus, by insects, fungi, and bacteria.

Most primary production of CO_2 is respired by plants, largely above ground. Root biomass (and presumably root respiration) is generally estimated at a third to a fourth of the total (35). The decrease we observed in below ground respiration is, therefore, only a fraction of the decrease of aboveground respiration. A large decline in aboveground productivity was measured in Eastern Amazonia by Uhl et al. (26, 27).

Accurate estimates of carbon turnover require good measures of underground gross and net production. Net production can be directly measured by biomass increments, but physiological respiration-rate measurements are required for the former. Tropical plants respire around 80 percent of carbon fixed, or about twice as large a fraction as temperate plants (7), so that they play a disproportionate role in the rate of global carbon cycling, the major control of atmospheric carbon dioxide residence time.

The importance of the terrestrial biota in the atmospheric carbon cycle has been historically obscured because terrestrial ecologists have emphasized the readily measurable quantity *net* primary production (less than half gross production), but marine chemists have focused on *gross* exchange of carbon dioxide across the air-sea surface (a number some fifty times greater than net exchange). Many carbon-cycle models have estimated soil sources of CO_2 to equal the net loss of soil humus (36), a number many times smaller than soil respiration. When terrestrial and marine ecosystems are compared on the same basis (5, 6, 37, 38) the flux of carbon dioxide to the atmosphere per unit area on land is considerably larger than that in the ocean.

Soils now release to the atmosphere about an order of magnitude more carbon dioxide than fossil-fuel combustion, so a decline from soils after deforestation might be erroneously thought beneficial, because it counteracts the buildup from combustion. A decrease in respiration will cause an immediate short-term decline in the rate of rise of carbon dioxide. Over the long term it causes a buildup of the gas in the atmosphere because it is part of a larger decrease in photosynthetic removal of carbon dioxide. This reduces atmosphere-biosphere recycling rates, increasing the atmospheric lifetime for carbon dioxide and decreasing the ability of the tropical biosphere to buffer increased combustion inputs. If carbon cycling in secondary habitats is generally reduced compared to primary ones (as would be expected except where there is adequate fertilization) then reduced biotic carbon cycling will cause fossil-fuel derived atmospheric carbon dioxide to reach higher levels, for longer periods, than would be the case in the absence of deforestation (14).

That such a reduction in productivity has occurred is made clear by contrasting current vegetation to descriptions of its primeval state almost anywhere on earth. Amazonia is still similar in many regards to it's first description by Carvajal in 1541–42 (39). But, most areas of the tropics (40) are, like the coastal rainforests of Brazil, surviving in only a percent or two of the original unbroken forest area (41). Over the remainder, erosion and soil degradation have made a mockery of de Magalhaes' 1576 (42) description: "the soil is very rich and fertile, entirely covered with exceedingly high leafy trees, whose verdure persists winter and summer; this is the reason for its raining often."

PRESERVING TROPICAL PRODUCTIVITY AND ECOPHYSIOLOGICAL FUNCTION

The oceans are a much less tractable sink for fossil-fuel carbon than the terrestrial biosphere. Even though they now hold a large amount in solution it is not readily in our power to alter oceanic-deep circulation rates, and climate warming will reduce the effectiveness of this sink by decreasing solubility of carbon dioxide and increasing stable temperature stratification. The intense rates of carbon recycling in tropical rainforests make their conservation and the upgrading of productivity in already degraded tropical habitats the most effective demand-side contribution to "managing" the global carbon-dioxide problem (14, 43, 44). Although current land-management practices are exacerbating the greenhouse problem, scientifically sound management practices, which could reverse the process, are already well known (45–51).

Conservation of the ability of tropical forests to cycle atmospheric carbon dioxide is a reason to preserve not merely the individual species (52), but the net physiological functioning of the entire ecosystem. Sadly, the major pool of terrestrial species complexity is now being replaced by a handful of species (in Central Amazonia one valueless genus of weed trees completely dominates abandoned sites), and tropical metabolism is being reduced by deforestation at a time when temperate ecosystems are stressed from

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widening forest dieback and declining growth rates, probably because of long-term pollution.

The adverse effects of deforestation on soil productivity and water balance (22, 53–56) have been known for many years. Brandao (57), described Maranhao, Brazil, in 1865, after massive deforestation was followed by semi-desertification: "This destruction of the forest has exhausted the soil, which in many places now produces nothing but grasses suitable for grazing cattle. The temperature has intensified, and the seasons have become irregular ... the streams have dried up or have become almost unnavigable." The problems of species loss, soil loss, nutrient loss, and hydrological alteration are not limited to land: tropical deforestation is now a major factor in destruction of coastal coral reefs through increased erosion and runoff (58). Reef ecosystems contain the bulk of all species in the sea as well as the highest productivity, highest respiration rates, and the highest limestone production rates per unit area of any marine ecosystem (58, 59). While they occupy a much smaller global surface area than rain forests, their gross productivity is exceedingly high, ranging from 15 to 55 tons of carbon per hectare per year (60), so their degradation further aggravates the global carbon dioxide and gene-pool conservation problems.

BALANCING THE CARBON CYCLE

A stable balance of atmospheric carbon dioxide can be achieved by combining control of combustion sources and by reversing terrestrial productivity decline by slowing deforestation and enhancing biological productivity of currently degraded tropical habitats through fertilization and replanting (44, 61). The Tropical Forest Action Plan recently proposed by the World Resources Institute, the World Bank, and the United Nations Development Program (62), while falling far short of what would be required to stabilize CO_2 levels in the atmosphere, is an essential first step in this direction.

A tree planting program focused on the tropics must include growth monitoring and intensive selection of fast growing economically useful plants to be effective. Such programs should be based in the tropical research institutions. While expensive compared to the present level of research funding in the area, this approach would be in everyone's long-term interest, being far cheaper than the alternatives such as unrestrained greenhouse-gas increase or drastic reductions in combustion sources.

Atmospheric carbon dioxide levels are already well above the maximum value they reached during the interglacial 125 000 years ago, when temperatures were warmer than today (63). Human-induced changes now exceed the capacity of historical natural controls, and only limited time remains to halt and stabilize the CO_2 buildup. Fortunately, it is in our power to do so, if we choose to make the resources available. Current practices maximize short-term profit by discounting long-term cost of ecosystem productivity. A mechanism is required to reward increases in productivity to levels sufficient to remove excess carbon dioxide from the atmosphere. As CO_2 production is a part of the real cost of fossil-fuel use that is not included in the price, the simplest mechanism would be to tax fossil-fuel use to a level that pays for removal of the CO_2 released (44). Only a global solution will work.

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