BRAZIL'S AMAZON FOREST AND THE GLOBAL CARBON PROBLEM

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The increase in the amount of carbon dioxide in the atmosphere is a major global concern because of the possibility of changing the world's climate. Present trends in use of fossil fuels and the expansion of agriculture into forested lands could lead to sufficient accumulation of CO_2 in the atmosphere before the middle of the next century to warm the earth an average of 1.5 - 4.5°C. Such a change would have major implications for the present regions of concentrated human habitation and for agricultural production [1]. The importance of tropical deforestation has been a focus of academic controversy in debate over the global carbon problem. Lack of reliable data on biomass, rates of deforestation, regeneration, and carbon release are the causes of such disagreements. Quantitative information about the Brazilian Amazon, with the planet's single largest tract of remaining tropical rainforest, has been particularly lacking. Here it is argued that deforestation in the Amazon could make a significant contribution to the larger global problem, and that the relative importance of deforestation is likely to grow as clearing continues in the coming decades. Although mean global temperature changes attributable to Amazon clearing may appear modest, they are added to an environmental strain on a system where the "camel's back" is very close to breaking.

The environmental impacts to be expected from a given temperature increase are an area of controversy. More important than mean temperature increase is the warming of polar regions, where higher temperature increases are expected than at lower latitudes. CO_2-induced temperature increase from all sources is eventually expected to melt polar ice, beginning with sea ice (Kukla and Gavin, 1981) and the West Antarctic ice sheet (Thomas *et al.*, 1979), raising mean sea level by 5 m (United States Council on Environmental Quality and Department of State, 1980; sea Marshall, 1981). Such a rise would flood many of the most populous parts of the globe, as well as much of the Amazon region. One point of wide agreement in the academic controversies surrounding almost all calculations related to CO_2 effects is that, once critical temperatures had been attained to begin melting polar ice, the long delays for equilibration of oceanic CO_2 would render ineffective any human countermeasures initiated at that late date, such as reduced CO_2 emissions.

The speed with which such a melting would occur is uncertain: the West Antarctic ice sheet might take several hundred years to melt, but could also melt completely in less than 100 years (Thomas *et al,* 1979; see also Mercer, 1978). One recent survey of expert opinion on the subject concludes that breakup would probably take several centuries, but that in the interim sea levels would rise at an accelerated rate of 70 cm per century (Kerr, 1983b). The West Antarctic ice sheet is vulnerable to more rapid melting than other Antarctic ice because floating ice shelves on its perimeter presently impede the sheet from undergoing a "surge" or accelerated sliding into the sea. The ice shelves are pinned against the Antarctic mainland by grounding on several rock highpoints or islands, forming ice rises. Should air temperatures increase, shelves such as the Ross ice shelf would melt more quickly than the terrestrial ice sheets, subsequently releasing the back pressure that now limits the rate of ice flow to the ocean from the major ice mass on the West Antarctic mainland. Uncertainty regarding the rate of breakup of the ice sheet if warmed stems from poor knowledge of the underlying topography and the probable drainage patterns of glaciers at the back of the sheet (Thomas *et al.,* 1979). Uncertainty about the rate of ice shelf breakup results from poor understanding of the effects of climatic changes on the salinity of

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surface waters, which affects the stability of ocean layers and the rate of heat transport from lower layers toward the surface (Schneider and Chen, 1980: 114).

Warming of about 5°C at the West Antarctic ice sheet would be required for melting. Although several climate models have predicted an increase of this magnitude to accompany mean global temperature increases on the order of 2°C from doubling of preindustrial CO_2 (Manabe and Stouffer, 1979; United States National Academy of Sciences, 1979; see Hansen *et al.*, 1981), disagreement surrounds the question of how great the warming in the polar regions will be relative to the global mean. Lian and Cess (1977) have made a strong case for reinterpreting earlier estimates of doubled effect (Budyko, 1969) to the much lower factor of 25%. Polar warming is magnified due to a positive feedback relationship between albedo (reflectivity) and ice cover, since melting ice exposes darker surfaces which absorb more heat. The polar region of the northern hemisphere is expected to be warmed more than that of the southern hemisphere due to the larger percentage of ocean and smaller seasonal change in snow cover (Kellogg, 1980: 219).

Although holding less potential for causing a large sea level rise than the West Antarctic ice sheet, melting of the northern hemisphere's arctic sea ice would bring substantial changes in global climate patterns. Doubling of preindustrial CO_2 is predicted by sea ice models to melt all of this ice in summer (Parkinson and Kellogg, 1979; see Hansen *et al.*, 1981). An open Arctic Ocean is an important factor in an expected shift of climatic zones poleward, disrupting agriculture in the Earth's present major grain producing latitudes (Flohn, 1974 see also Schware and Kellogg, 1982). Similar poleward shifts also occur in climate simulations where idealized geography eliminates an explicit Arctic ocean by assuming constant proportions of water and land at all latitudes (Manabe and Wetherald, 1980).

The amount by which specific regions of the globe would be wetter or dryer is a matter of some uncertainty. The suggestion has been made that a number of presently dry regions of the globe would be benefitted, including northeastern Brazil, at the same time that other areas, including southern Brazil and most of the Amazon rainforest area, would become dryer (Schware and Kellogg, 1982). Northeastern Brazil's Rio São Francisco, however, is expected to be one of the Earth's many rivers presently supporting irrigated agriculture to suffer decreased water flow (Revelle, 1982).

Uncertainties remain in assessing the potential impact of Amazonian deforestation on the global carbon problem, but these are small in relation to the total impact. Incomplete release is one such uncertainty. Part of the carbon in tropical forest aboveground biomass is converted to charcoal at the time of burning, thereby removing some of the carbon inventory to a long-term pool where it could only be converted to CO_2 on a time scale of millenia. Measurements of this carbonization factor do not yet exist, although data analysis is underway for observations of carbon transfer to this and other pools in a burn studied by INPA in forest felled for pasture near Manaus in 1984. The carbonization factor for use with total biomass conversion should include not only the charcoal formed during the initial burning of the felled forest, but also the charcoal formed during subsequent burns of pasture and secondary forest. The great variability that characterizes burn quality in Amazonia means that measurements in a number of burns would be needed in order to obtain parameters for climate models. One set of values that has been used in such models was derived by Goudriaan and Ketner (1984: 178-179) from Seiler and Crutzen's (1980) rough visual estimates of charcoal formation in a north temperate forest fire in a stand of ponderosa pine *(Pinus ponderosa)*. Goudriaan and Ketner (1984) use carbonization factors of 5% for leaves, 10% for branches and 20% for stems; these parts making up 30%, 20% and 30% respectively of the total biomass, or 37.5%, 25.0% and 37.5% respectively of the aboveground biomass in tropical forest. A weighted carbonization factor for the aboveground biomass would therefore be 11.9%. Were this factor applied to the 60.09 G tons of total carbon in aboveground forest biomass in the Brazilian Amazon (Table I), the total carbon release (from aboveground biomass + surface soil) from replacement of the forest by pasture would be 54.69 G tons. Preliminary impressions are that the carbonization factor is somewhat lower than Goudriaan and Ketner's (1984) 11.9% meaning that the true release of carbon to the atmosphere from conversion to pasture would lie somewhere between 54.69 and 60.09 G tons.

Carbon release would also be tempered by the biomass stock in the second growth that would presumably dominate degraded pasture lands within a decade or two of conversion from primary forest. Studies of secondary forest biomass accumulation as related to soil fertility are being carried out by INPA in Pará and Rondônia. Despite uncertainty regarding the equilibrium stock of carbon in replacement vegetation, rainforest clearing would be sufficiently great that even if the average biomass in replacement vegetation were to attain, say, 50% of the original biomass — a figure unlikely to be reached on average over the region — a climatically significant net CO_2 release would still occur.

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Immediate Effects

If the entire Brazilian Amazon were cleared and burned with an assumed 25% combustion of dead and live above ground biomass, approximately 11.35 gigatons (10^9 metric tons = G tons) of carbon would be released. The fraction of the biomass converted to CO_2 is uncertain as no measurements exist. Silva (1978) used an estimate of 20% combustion: Seiler and Crutzen (1980) used 25%. For the purposes of calculation, I have adopted value assumed by Seiler and Crutzen (1980). Observations on burns in the Brazilian Amazon indicate that the fraction burned varies greatly both between farmers and from year to year (Fearnside, nd-a).

The amount of human-induced CO_2 remaining in the atmosphere is uncertain by a factor of 2 due to doubt concerning preindustrial CO_2 concetration. If the preindustrial level was 290 ppmv (parts per million by volume), then 70 G tons has remained but if the concentration was 260 ppmv then twice that amount has remained, calculating from a total human input of 180-260 G tons (Bolin *et al.*, 1979a). The lower figure for preindustrial CO_2 will be used here, as values in this range have been suggested as reasonable based on presumed slow uptake by the large portion of the world's vegetation that is not limited by CO_2 (Goudriaan and Ajtay, 1979 see Björkström, 1979a: 448), and by isotopic ratioing evidence from tree ring carbon (Stuiver, 1978). Air bubbles trapped in Arctic and Antarctic ice since preindustrial times contain about 270 ppmv CO_2 (H. Oeschger and B. Stouffer, quoted by Kerr, 1983a). Recent reexamination of late nineteenth-century CO_2 measurements made in Europe and South America strongly indicates a preindustrial value in the 260-270 ppmv range (Wigley, 1983). Indirect support for the lower preindustrial CO_2 levels is given by global carbon cycle simulations that only produce reasonable fits to historical $^{13}C/^{12}C$ time series data if a preindustrial CO_2 of approximately 245 ppmv is assumed (Emanual *et al.*, 1984).

Using a current remaining fraction of 54-78% for cumulative total (fossil + nonfossil) carbon, calculated from the estimate by Bolin *et al.*, (1979a: 49) for the 260 ppmv preindustrial CO_2 case, 6.13-8.85 G tons C would remain in the atmosphere [2]. The present calculation is optimistic in assuming a fixed remaining or cumulative airborne fraction: in reality the airborne portion of future inputs is expected to rise as absorption capacity of the oceans is saturated due to future CO_2 increases. Keeling and Bacastow (1977; see Bolin *et al.*, 1979a: 47) have estimated that the airborne fraction (ignoring sources from changes in the biota) may increase to above 80%. A series of models of atmospheric CO_2 concentration by Siegenthaler and Oeschger (1978) have produced simulated values for the airborne fraction of the cumulative CO_2 releases (from fossil fuels only) on the order of 80% if all fossil fuel reserves are burned, and values ranging from 55.5% to 71.1% if an approximate doubling of preindustrial CO_2 were to occur by 2020. Such increases in the airborne fraction would magnify the climatic impact of each ton of carbon released.

Since the current atmospheric CO_2 concentration of 330 ppmv corresponds to 700 G tons of carbon (Björkström 1979b), the mean atmospheric increase from the relatively rapid release accompanying initial burning of Brazil's Amazon forest would be about 2.9-4.2 ppmv. Mean global temperature increases from the "greenhouse effect" of this carbon input can be estimated roughly using the 1.5-4.5°C range suggested by the United States National Academy of Sciences (1979) for the effect of doubling a 300 ppmv preindustrial CO_2 concentration. Mean effects of doubling predicted by most global climate models fall in this range, including the estimates of 2-3°C by Manabe and Wetherald (1967, 1975) and 2°C by Manabe and Stouffer (1979). These models include a positive feedback process between ocean temperature and tropospheric warming which magnifies the effect of CO_2 on global surface temperatures: increased ocean surface temperature releases water vapor, which in turn absorbs solar radiation and re-emits it as infrared (IR). The fraction of this IR emission that is directed downward further warms the ocean surface (Ramanathan, 1981). Global climate models omitting this feedback process (Newell and Dopplick, 1979), or alternatively short-term observations over continental land masses (Idso, 1980), conclude that a doubling of CO_2 would have negligible effect on mean global temperatures, whereas the various models which include the feedback show warming in the range indicated (see Kerr, 1982; United States National Academy of Sciences, 1982; Ramanatham, 1981). The initial burning would account for 0.01-0.06°C of this global warming [3].

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Delayed Effects

The ultimate total carbon release from deforesting the Amazon depends on the land use replacing the original vegetation. The great majority of cleared area in the Brazilian Amazon is converted to cattle pasture within a few years of felling (Fearnside, 1983). pasture is unlikely to replace all woody growth as invasion by woody species is common in the current first cycle of what could become a sort of low-productivity shifting ranching system (Fearnside, 1979, 1980). In a manner analogous to shifting cultivation, pastures are temporarily abandoned when productivity falls to unacceptable levels. Unfortunately, the regrowth of woody vegetation on degraded pasture land is much slower than regrowth in fields fallowed under long cycle shifting cultivation, and the regrowth is unlikely to be permitted to reach a high proportion of the original forest biomass before reclearing. The argument sometimes advanced that the rapid regeneration of biomass characteristic of shifting cultivation fallows would substantially counterbalance carbon releases from deforestation in areas like the Brazilian Amazon [4] is therefore misleading. In Amazonian Brazil, area occupied by shifting cultivation is minor relative to the rapidly expanding area of pasture (Fearnside, nd-b). Nevertheless, some amount of carbon will undoubtedly be retained in secondary forests in the coming decades.

Another poorly-quantified carbon sink is the charcoal produced during burning. Seiler and Crutzen (1980) have argued that storage of carbon as charcoal in the soil significantly lowers the impact of land clearing on atmospheric CO_2. Houghton *et al.* (1983) have conducted sensitivity tests of a bookkeeping model of carbon stores (Moore *et al.*, 1981) arriving at the conclusion that, if undisturbed forest can be assumed to be in steady state with respect to carbon, charcoal "is not important, except as the rate of burning and formation is changing currently." Houghton *et al.* conclude from their analysis that the largest source of atmospheric carbon is conversion of forests to agriculture, especially in the tropics (see also Hobbie *et al.*, 1984; Woodwell *et al.*, 1983). Deforestation is a significant factor even when the modifying influence of charcoal emphasized by Seiler and Crutzen (1980) is assumed: when the values of these authors for charcoal and other parameters were used as the basis for a simulation of the global carbon cycle, the life span of biomass and the rate of deforestation and land reclamation were found to be two of the three most important uncertainties affecting atmospheric CO_2 levels in the next century (Goudriaan and Ketner, 1984: 189).

Most of the biomass left uncombusted by the first burn following felling is oxidized within a decade or two through decay and combustion as agricultural fields and pastures are reburned in succeeding years. Increased termite activity in cleared areas provides an additional route for CO_2 release (Zimmerman *et al.*, 1982; but see criticism by Collins and Wood, 1984 and rebuttal by Zimmerman *et al.*, 1984). Impact of these delayed releases on atmospheric CO_2 and global temperatures would be about 6 times as great as the immediate effects. The accumulated release would reach 61.8 G tons C as a result of decline in the carbon stored in total biomass under natural vegetation (Table I) to the 2 metric tons per hectare wet weight biomass[5] (= 0.21 G tons C in Brazil's *Amazonia Legal)* under 10 year old pasture at Paragominas, Pará (Hecht, 1982: 355), together with decrease in soil carbon in the top 20 cm by the amount observed to result from conversion of forest to pasture. Soil organic matter declines rapidly following clearing due to increased soil temperatures shifting the equilibrium value to a lower level (Cunningham, 1963; Nye and Greenland, 1960). Using means of soil carbon under 10 and 11 year old pasture at Paragominas and Suiá-Missu (Falesi, 1976: 31 and 42), a decrease could be expected from 0.91% of dry weight in the top 20 cm of soil under forest (mean for the same two areas) to 0.56% under pasture. For *Amazônia* Legal (5 x 10^6 km^2), this would release 1.96 G tons C from the top 20 cm of forest soil, using a value for soil density of 0.56 g cm^{-3} under forest at Paragominas (Hecht, 1981: 95). The pasture soil surface layer used in this calculation is that compacted from the upper 20 cm of forest soil, not the layer of identical vertical dimension under pasture. Soil carbon loss figures are conservative: deeper layers are ignored.

Total CO_2 increase from immediate and delayed carbon releases would be 15.7-22.7 ppmv, using the same assumptions regarding the fate of carbon in the atmosphere as those used in calculating immediate effects. These calculations are conservative in ignoring any potential effect from disruption of the annual cycle of carbon flux between the biosphere and the atmosphere. Annual carbon flux between the atmosphere and the biosphere totals approximately 63 G tons, as compared to 5 G tons from fossil fuels (Bolin *et al.*, 1979b: 5). The importance of biosphere flux is indicated by annual CO_2 concentration cycle in northern hemisphere as compared to the South Pole (Keeling *et al.*, 1976b; see also Woodwell *et al.*, 1978). The greater proportion of land in the northern hemisphere accounts for the larger seasonal oscilation. Disruption of the atmosphere to biosphere flux is considered potentially serious, since even a slight decrease in the ability of land biota to absorb carbon through photosynthesis would create a significant imbalance (Henderson-Sellers, 1981: 454).

The delayed carbon releases from a deforested Brazilian Amazon would bring the total increase in global mean temperature to 0.08-0.34°C, following the calculation procedure used for immediate effects. Extending these calculations to the entire Amazon drainage basin would increase the values by about 56% (bringing mean temperature rise to 0.12-0.53°C), using 7.8- 10^6 km^2 as the area of the Amazon drainage (Henderson-Sellers, 1981) and 5 x 10^6 km^2 for the Brazilian Legal Amazon.

Carbon release to the atmosphere adds to the substantial list of probable negative biological and human impacts from large-scale deforestation

Discussion

Academic controversies surround many points touched by the above arguments. The data on Amazon forest biomass used in the present calculations are taken from published studies for specific localities. The main component of the biomass total in the region — upland dense forest — is derived as a mean from studies reporting measurements in two widely-separated portions of the region; the biomass values used for each of these portions of the region, in turn, is a composite of several studies (Table I, note d). The total upland dense forest biomass for the three fractions — live above-ground, below-ground, and litter + dead above-ground — is 361.5 m tons ha^{-1} (Table I). A recent estimate based on timber volume inventories and allometric relationships claims a mean of only 155.1 m tons ha^{-1} (or about one-half of the present estimate) for the apparently equivalent category of "tropical American closed undisturbed productive broadleaf forests" (Brown and Lugo, 1984). Such a value is substantially lower than any available values from actual measurements. What information exists for portions of the Brazilian Amazon not included in the present estimate, such as the 354 m tons ha^{-1} of "wood" biomass estimated for the forests of the Jari Project area (Jordan and Russell, 1983), confirms the higher value of Table I. It is worth noting, however, that climatically significant amounts of carbon would be released by clearing the region's forests even if the much lower timber-volume-based estimate were to prove correct.

Controversy also surrounds the entire enterprise of predicting CO_2-induced warming from general circulation models of the atmosphere. Discrepancies between many model results and observed temperature trends have been reviewed by Idso (1983). Despite whatever shortcomings existing models may exhibit, the logic supporting a potentially significant CO_2-induced "greenhouse effects" is quite convincing. The present discussion bases its conclusions on likely temperature changes from a given CO_2 rise on the syntheses provided by the panel of experts assembled by the United States National Academy of Sciences (1977, 1979, 1982).

Atmospheric CO_2 increases are cumulative. Apportioning of blame between deforestation and other sources does nothing to diminish the severity of the problem as a whole. Neither does the existence of multiple contributors to atmospheric CO_2 render futile activities aimed at alleviating any particular portion of the problem. With these considerations in mind, it is worthwhile examining how CO_2 release from Amazonian deforestation compares with that from fossil fuel combustion at present, and how the relative importance of these contributors is likely to change in the future.

Amazon rainforest clearing is a minor factor relative to fossil fuels when comparisons are made either of present inputs from rainforest burning to present global fossil fuel inputs, or of ultimate total inputs from completely combusting rainforest and fossil fuel stocks. Focus on either the small current net releases from the earth's biota *(e.g.* Broecker *et. al.*, 1979) or on hypothetical total releases from combustion of fossil fuel reserves *(e.g.* Clark *et al.*,

TABLE I

BIOMASS AND CARBON STORE OF "NATURAL" VEGETATION IN BRAZIL'S LEGAL AMAZON

			Live Above Ground			*Below Ground*			*Litter and Dead Above Ground*		
Vegetation Type	Area (km^2)	Reference	Dry Phytomass (m tons ha−1) (a)	Reference	Carbon (b) (G tons)	Dry Phytomass (m tons ha−1) (a)	Reference	Carbon (b) (G tons)	Dry weight (m tons ha−1) (a)	Reference	Carbon (b) (G tons)
Upland Dense Forest	3,063,000	(c)	251.7	(d)	34.69	86.3	(e)	11.90	23.5 (c)	(e)	3.239
Scrub Forest *(cerrado)*	1,290,520	(c)	37.8	(g)	2.20	25.2	(g, h)	1.46	7.7	(g, h)	0.450
Montane Forest	26,000	(c)	198.0	(i, p. 53)	0.23	64.8	(i, p. 53)	0.08	3.15	(i, p. 65)	0.004
Other Upland Forest types	259,000	(c, j)	277.5	(g)	3.23	70.3	(g, h)	0.82	22.2	(e. h)	0.260
Humid Savanna (upland + flooded)	165,000	(c)	71.5	(g)	0.53	31.9	(g, h)	0.24	6.7	(g, h)	0.050
Flooded Forests *(Várzea + Igapó)*	70,000	(c)	158.1	(k)	0.50	54.2	(f, k)	0.17	3.34	(k)	0.011
Mangroves	1,000	(c)	162.5	(1)	0.01	190.0	(1)	0.01	102.1	(1)	0.005
TOTAL	4,874,520				41.39			14.68			4.02

Total carbon — 60.09 G tons

(a) All dry weights approximated using correction factor of 0.475 m tons dry/m ton wet (midpoint of range used by Klinge *et al.* 1975).

(b) Carbon content of 0.45 used for all biomass (Woodwell *et al.*, 1978; Golley, 1975; 106 cited by Hampicke, 1979: 219).

(c) Braga, 1979.

(d) Average of estimates for two portions of Amazonia: the Tucuruí Reservoir area, Pará (247.84 m ton ha−1 live above ground phytomass dry weight), and "Central Amazonia" high forest near Manaus (255.60 m tons ha−1). Tucuruí estimate is weighted mean of 4 types of high nonriparian forest in the proportions occuring in the reservoir area (Brazil, ELETRONORTE and SEPLAN-CNPq-INPA, 1981; Cardenas *et al.*, 1982), while Central Amazonia estimate is unweighted mean of 6 studies in the Manaus area: the phytomass weighed by Klinge and Rodrigues (1974) and estimates made by Klinge and Rodrigues (1974) as extensions of their study to 5 nondestructive quadrat and transect forest surveys available in the literature (Takeuchi, 1961; Lechthaler, 1956; Aubreville, 1961; Rodrigues, 1967; Soares (1957) cited by Aubreville (1961).

(e) Klinge *et al.*, 1975.

(f) Calculated assuming same ratio to live above ground phytomass (dry weight) as in upland dense forest at Manaus: 353.4 m tons ha−1 live above ground: 121.1 m tons ha−1 below ground: 33.0 m tons ha−1 litter and dead above ground (7.6 m tons ha−1 standing dead wood + 18.2 tons ha−1 fallen dead wood + 7.2 m tons ha−1 fine litter) (Klinge *et al.*, 1975).

(g) Seiler and Crutzen, 1980.

(h) Calcualted using percent underground, above ground dead and litter phytomass for these vegetation types given by reference indicated.

(i) Pires, 1973.

(k) Rio Tocantins (a clearwater river) flooded forest at Tucuruí Reservoir, Pará (Cardenas *et al.*, 1982).

(1) Mangrove values from Panamá (Golley *et al.*, 1975).

1982) is misleading as a guide to the potential impact of deforestation in the coming decades. Carbon in total global "available" fossil fuel reserves is estimated at 5000 G tons (Perry and Landsberg, 1977 cited by Bolin *et al.*, 1979a: 33). At the current annual fossil fuel carbon input rate of 5 G tons (Bolin *et al.*, 1979a), release of the Amazon forest and soil stock from complete combustion and conversion to pasture (60.09 G tons forest above ground G - 0.21 above ground under pasture = 59.88 G tons release from above ground biomass, + 1.96 G tons from soil = 61.84 G tons) would represent 12 years of fossil fuel use, while incomplete release would represent proportionately less. However, if rainforest clearing is rapid during the coming few decades, the relative impact of this process will assume greater importance during the brief period while continued existence of substantial rainforest stands allows clearing to proceed. Estimates of current *annual* carbon release from tropical deforestation include 0.6-1.1 G tons (Seiler and Crutzen, 1980: 235), 1.3 G tons (Loucks, 1980: 23), 1.75 G tons (Bach, 1980: 160), and 1-7 G tons (Woodwell *et al.*, 1978). Although the largest of these estimates has been criticized as irreconcilable with rates of oceanic uptake (Broecker *et al.*, 1979), and as ignoring sinks such as soil charcoal (Seiler and Crutzen, 1980), even the highest estimates of current deforestation input rates are dwarfed by potential releases accompanying likely increases in rainforest clearing. For example, if release of the approximately 62 G tons of carbon implied by conversion of Brazil's Amazon forest to pasture were to occur in as many years, a rate far slower than that implied by current trends (Fearnside, 1982, 1984), then the resulting 1 G ton C year^{-1} average release would represent 20% of the current fossil fuel release. Release of the Amazon rainforest's store of carbon at double this rate is not beyond the range of possibility.

Conclusions

1.) Clearing of Brazil's 5 x 10^6 km^2 *Amazônia Legal* would release approximately 11 G tons C to the atmosphere immediately, followed by a slow release raising the total to about 62 G tons.

2.) These immediate and total carbon releases correspond to contributions of 0.01-0.06 °C and 0.08-0.34 °C respectively to mean global temperature increase, according to calculations based on a number of assumptions. It is emphasized that data are scarce on biomass, burning efficiencies, charcoal and other factors in the Amazon region, and that uncertainties in the present understanding of the global carbon problem also apply to the above calculations. These calculations are made in the context of anticipated fossil fuel combustion bringing total atmospheric CO_2 concentration to double the preindustiral level.

3.) The rapid pace of clearing makes the likely importance of deforestation relative to fossil fuels much greater in the coming decades than either carbon inputs from the recent past or ultimate total inputs would imply.

4.) Carbon release to the atmosphere adds to the substantial list of probable negative biological and human impacts from large-scale deforestation [6].

NOTES

1. United States National Academy of Sciences (1977, 1979), see Wade (1979); United States Council on Environmental Quality and Department of State (1980) see Marshall (1981); United States National Academy of Sciences (1982) see Kerr (1982); Flohn (1974).

2. A wide variety of values have appeared in the literature for the "airborne fraction," or the share of released CO_2 that remains in the atmosphere rather than being incorporated into living organisms, or transferred to nonliving sinks such as ocean sediments. Two sources of potential confusion make care necessary in interpreting these values. One problem is the base used far calculating the fraction, which can refer either to the inputs from fossil carbon alone, or to total inputs (fossil + nonfossil carbon). Values for total carbon alone are higher than those for total carbon by a factor of about 60%. Since fossil fuel releases are relatively much better documented than are releases from deforestation and other nonfossil sources, airborne fraction values for fossil carbon (*i.e.* that falsely assume no net carbon flux from the biota) are more common.

   A second problem is the preindustrial CO_2 level assumed in making the airborne fraction estimate. Those that assume a preindustrial CO_2 level of around 290 ppmv, as was standard for the earlier climate models, arrive at a value for the airborne fraction about half that of those that base the calculation on a preindustrial CO_2 level of around 260 ppmv (Bolin, 1979a: 49). Other values appearing in the literature for the airborne fraction for total carbon include: 36% based on a preindustrial CO_2 level of 295 ppmv (Fryer, 1978, cited by Fryer, 1979, 90); 40-50% (Revelle and Munk, 1977, cited by Revelle, 1982: 41); 62% (Hampicke, 1980: 1956); 35-45%, based on a preindustrial CO_2 level of 275 ppmv (Bolin, 1977: 615); and 27-39%, based on a pre-industrial CO_2 level of 290 ppmv (Bolin *et al.*, 1979a: 49).

   It should be remembered that the assumption of a constant airborne fraction is an artifact of the standard practice of applying to a single year a fraction calculated over 25 to 100 years. Time is critical to the airborne fraction; the only reason the fraction may not have changed since the mid-nineteenth century is that the growthrate of fossil and non-fossil sources of CO_2 to the atmosphere may have been exponential since then (R. A. Houghton, personal communication, 1985).

3. Note that these calculations assume that deforestation occurs in the context of a doubling of preindustrial CO_2 due to releases from all sources. Such a doubling has been projected to occur by the years 2025 if fossil fuel consumption continues to grow at the 4% year^{-1} mean that characterized the 1940-1973 period (Marshall, 1981 citing United States Council on Environmental Quality, 1981) or 20 years later if consumption were to grow at half that rate (Wade, 1979 citing United States National Academy of Sciences, 1979). At atmospheric CO_2 levels other than twice the preindustrial level the effect of any given carbon release would be different. The impact of each additional gigaton, as well as the impact of all previous gigatons, will increase as transfer pathways to various sinks are saturated at high levels of CO_2.

4. Lugo and Brown, 1981; Brown and Lugo, 1980 cited by Lugo and Brown, 1982; Brown and Lugo, 1982.

5. A recent finding of 2.5 metric tons ha^{-1} live above ground biomass in 2-year-old grazed pasture, plus 6 metric tons ha^{-1} of litter (Buschbacker, 1983) implies a somewhat smaller although still substantial biomass reduction.

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