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GREENHOUSE GASES FROM DEFORESTATION IN BRAZILIAN AMAZONIA: NET COMMITTED EMISSIONS

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Abstract. Deforestation in Brazilian Amazonia is a significant source of greenhouse gases today and, with almost 90% of the originally forested area still uncleared, is a very large potential source of future emissions. The 1990 rate of loss of forest (13.8 X 10^3 km^2/year) and cerrado savanna (approximately 5 X 10^3 km^2/year) was responsible for releasing approximately 261 X 10^6 metric tons of carbon (10^6 t C) in the form of CO_2, or 274-285 X 10^6 t of CO_2-equivalent C considering IPCC 1994 global warming potentials for trace gases over a 100-year horizon. These calculations consider conversion to a landscape of agriculture, productive pasture, degraded pasture, secondary forest, and regenerated forest in the proportions corresponding to the equilibrium condition implied by current land-use patterns. Emissions are expressed as "net committed emissions," or the gases released over a period of years as the carbon stock in each hectare deforested approaches a new equilibrium in the landscape that replaces the original forest. For low and high trace gas scenarios, respectively, 1990 clearing produced net committed emissions (in 10^6 t of gas) of 957-958 for CO_2, 1.10-1.42 for CH_4, 28-35 for CO, 0.06-0.16 for N_2O, 0.74-0.74 for NO_x and 0.58-1.16 for non-methane hydrocarbons.

1. INTRODUCTION

The present paper offers a structure for analyzing the greenhouse gas contribution of deforestation in Brazilian Amazonia (Figure 1). It is hoped that this structure will prove valuable beyond the short time that the series of numbers for greenhouse gas emissions presented here remains the current best estimate. As the rates and locations of deforestation activity change, and as better data become available on these and other important factors, the estimates can be continually updated. Deforestation rates declined over the period from 1987 to 1991, but this is largely explained by Brazil's deepening economic recession, and cannot be extrapolated into the future (Fearnside, 1993a).

(Figure 1 here)

A variety of measures exists for expressing greenhouse gas emissions from tropical deforestation (see Makundi et al., 1992). One of these is net committed emissions, which considers the emissions and uptake that will occur as the landscape approaches a new equilibrium condition in a given deforested area (here the 13.8 X 10^3 km^2 of Brazil's Amazonian forest that was cut in 1990). The "prompt emissions" (emissions entering the atmosphere in the year of clearing) are considered along with the "delayed emissions" (emissions that will enter the atmosphere in future years), as well as the corresponding uptake as replacement vegetation regrows on the deforested sites. Not included are trace gas emissions from the burning and decomposition of secondary forest and pasture biomass in the replacement landscape, although both trace gas and carbon dioxide fluxes are included for emissions originating from remains of the original forest biomass, from loss of intact forest sources and sinks, and from soil carbon pools. Net committed emissions are calculated as the difference between the carbon stocks in the forest and the equilibrium replacement landscape, with trace gas fluxes estimated based on fractions of the biomass that burn or decompose following different pathways.

Net committed emissions are not the same as the annual balance of emissions from the region. An annual balance calculation would consider the entire region (not just the part deforested in a single year), and would consider the fluxes of gases entering and leaving the region both through prompt emissions in the newly deforested areas and through the "inherited" emissions and uptakes in the clearings of different ages throughout the landscape. Inherited emissions and uptakes are the fluxes occurring in the year in question that are the result of clearing activity in previous years, for example, from decomposition or reburning of the remaining biomass of the original forest. The annual balance also includes trace gases from secondary forest and pasture burning and decomposition. The Framework Convention on Climate Change, signed in Rio de Janeiro in June 1992 by 155 countries plus the European Union, requires national estimates of fluxes and stocks for use in calculating the annual balance of emissions for each country. Presumably, the annual balance will form the basis for assigning responsibility for global warming in any protocols that may be negotiated under the Framework Convention.

Net committed emissions has several advantages over the annual balance as a measure of the impact of tropical deforestation, for example, for purposes of comparing the impacts of deforestation to those of fossil fuel combustion. Burning fossil fuels releases all gases in a single pulse, whereas deforestation sets in motion a process that commits emissions for a number of years after the trees are cut. Comparisons limited to prompt emissions from the two sources therefore grossly understate the impact of deforestation. The inherited emissions included in the annual balance avoids much of this distortion, but changes in the deforestation rate alter its appropriateness as a measure of the importance of deforestation. When clearing rates are increasing, the annual balance will understate the impact of deforestation, and when clearing rates are decreasing, it will overstate it. Except for the relatively small contribution of trace gases from secondary forest and pasture biomass, the annual balance and net committed emissions would be equal if deforestation rates were constant over an extended period of years. Using net committed emissions as a measure of the importance of deforestation is a more appropriate measure than the annual balance for assessment of deforestation policy questions in terms of the global interest (as opposed to each country's national interest under the Framework Convention).

Although better than the annual balance, net committed emissions is not ideal as the measure of deforestation's impact. The time when emissions occur is important, as human societies place a higher value on avoiding short-term impacts than on impacts far in the future. Although this preference is reflected in the time horizon of the global warming potentials used to express different trace gases in terms of carbon dioxide equivalents, the computations only include time preference with respect to the atmospheric load originating from a single pulse of gas, not the timing of the fluxes themselves in the case of delayed emissions. To the extent that deforestation has remained constant, net committed emissions are the same as the annual balance and knowledge of the timing of releases becomes unnecessary, thus greatly simplifying both data requirements and computation. A better index than net committed emissions would be provided by what may be called "time preference weighted emissions"--a measure derived from a non-equilibrium calculation using explicit fluxes for each year in the cleared area, and weighting these using both a time horizon and a scheme for assigning time preference (as by discounting or other alternative procedures). Discount rates or other time preference adjustments appropriate for such calculations are unlikely to be the same as those employed in financial analyses (Fearnside, 1995a).

2. EXTENT AND RATE OF DEFORESTATION

The present paper uses estimates of the extent and rate of deforestation by state derived from LANDSAT imagery (Tables I and II). The cumulative area deforested through 1991 had reached 427 X 10^3 km^2 (including old clearings and hydroelectric dams), or 10.7% of the 4 X 10^6 km^2 originally forested portion of Brazil's 5 X 10^6 km^2 Legal Amazon region. Forest loss from 1978 through 1988 proceeded at an average of 20.4 X 10^3 km^2/year (Fearnside, 1993b); this rate estimate is derived, with a variety of adjustments, from estimates of deforestation extent in 1978 (Skole and Tucker, 1993) and in 1988 (Fearnside *et al.*, 1990, see Fearnside, 1993a). Deforestation rate fell to 19.2 X 10^3 km^2/year in 1989, 13.8 X 10^3 km^2/year in 1990, and 11.1 X 10^3 km^2/year in 1991 (Brazil, INPE, 1992, see Fearnside, 1993a). The 1991 rate of forest loss was 20% less than the 1990 rate on which the emissions calculations in this paper are based.

(Tables I and II here)

The above rates cover only loss of primary forest within the portion of the region that was originally forested. Rates of conversion of the nonforest area, mainly *cerrado* (central Brazilian dry scrub savanna) are far less certain, but fortunately have less impact on greenhouse gas calculations due to the much lower biomass of savanna vegetation. The *cerrado* clearing rate for 1990 is assumed to be 5 X 10^3 km^2/year, a value lower than the 10 X 10^3 km^2/year used previously for 1990 (Fearnside, 1992a), and much lower than the 18 X 10^3 km^2/year estimated for 1988 (Fearnside, 1990). Based on comparison of Brazil's 1970 and 1985 agricultural censuses, Klink *et al.* (1994) estimated that 20 X 10^3 km^2/year of *cerrado* were cleared over that period, including areas outside of the Legal Amazon. The *cerrado* loss rate used in my present emissions estimate is believed to be conservative.

The rate of deforestation, together with the biomass of forest being cleared, affects the current (as opposed to potential) contribution of deforestation to the greenhouse effect. The rate of clearing has been calculated for each state (Table II), and is apportioned among various forest types within each state by assuming that, within each state, each forest type is cleared in proportion to the area in which it occurs outside of protected areas.

3. BIOMASS OF AMAZONIAN FORESTS

The initial biomass of the vegetation is an important factor affecting the magnitude of greenhouse gas emissions from deforestation. The biomass estimate used in the present paper-- 434 metric tons per hectare (t/ha) pre-logging total biomass for forests cleared in 1990 [post-logging biomass is 407 t/ha]--is based on much more data than earlier estimates and is derived as a weighted average from estimates that are disaggregated by state and forest type. The estimate indicates a substantial increase in biomass per hectare estimated for locations currently the focus of deforestation activity in Amazonia. It more than doubles the 155.1 t/ha value for total biomass derived by Brown and Lugo (1984) from FAO forest volume surveys for "tropical American undisturbed productive broadleafed forests" that has been used in recent global carbon balance calculations (e.g., Detwiler and Hall, 1988). It is also much higher than the 169.8 t/ha above-ground estimate by Brown et al. (1989) used as total biomass by Houghton (1991) for carbon emission estimates. Hall and Uhlig (1991) used the volume and expansion factor from the Brown et al. (1989) study, plus a correction for below-ground biomass, to obtain an estimate of 98.2 t C/ha (196.4 t biomass/ha) for undisturbed forests in "Brazil." The estimate used in the present study is also higher than the 211 t/ha total biomass estimated for areas cleared in 1988 for emissions calculations (Fearnside, 1991); a major reason for the increase is better data (derived from forest inventories of Brazil, Projeto RADAMBRASIL, 1973-1983) for biomass in the southern portion of the region where deforestation activity is concentrated. The estimate also has improved information on wood density and on below-ground biomass.

The different types of vegetation present in the Legal Amazon have been measured (Fearnside and Ferraz, 1995) from a digitized version of the 1:5,000,000 scale vegetation map of Brazil published by the Brazilian Institute for Geography and Statistics (IBGE) and the Brazilian Institute for Forestry Development (IBDF--since incorporated into the Brazilian Institute for the Environment and Renewable Natural Resources - IBAMA) (Brazil, IBGE and IBDF, 1988). The IBGE/IBDF (IBAMA) map code used indicates 28 vegetation types within the Brazilian Legal Amazon, of which 19 are considered here to be forest (Table III). This is a liberal definition of forest, including all ecotones between a forest and a nonforest vegetation type such as cerrado. So defined, the area of forest present according to the map totals 3.7 X 10^6 km^2, or 74% of the 5 X 10^6 km^2 Legal Amazon. The area originally forested totals 4.3 X 10^6 km^2 (Table IV). The areas that were originally forest and nonforest using this definition are mapped in Figure 2. The deforestation estimate used here has as its base a definition of originally forested area corresponding to approximately 4.0 X 10^6 km^2, therefore implying some remaining inconsistency.(*)

(Tables III and IV and Figure 2 here)

Because the Legal Amazon is so big, each of its nine states being the size of countries in many parts of the world, vegetation with the same map code in different states cannot be assumed to have the same biomass. Considering each vegetation type in each state as a separate unit, here designated "ecoregions," there are a total of 111 different ecoregions in the Legal Amazon, of which 78 are "forest."

In order to estimate the area of each forest type being cleared annually in 1990, it was assumed that forests within each state are cleared in proportion to the area of each type (outside of parks and other legally protected areas). Although protected areas are not immune to deforestation, the small amount of clearing activity currently taking place inside these areas is undoubtedly insignificant from the standpoint of greenhouse gas emissions.

All biomass values given here and elsewhere in this paper refer to oven dry weight biomass. Unless otherwise noted, values are for total biomass, including both above- and below-ground portions, and including dead vegetation (but not soil carbon). All biomass fractions are included (leaves, small trees, vines, understory, etc.). Values are expressed in terms of biomass, rather than carbon (carbon content of biomass is 50%).

Biomass loading (biomass per hectare) of the different forested ecoregions is estimated from forest volume inventories in surveys carried out by the RADAMBRASIL project in the 1970s (Brazil, Projeto RADAMBRASIL, 1973-1983) and by the Food and Agriculture Organization of the United Nations (FAO) in the 1950s (Glerum, 1960; Heinsdijk, 1957, 1958a,b,c). A total of 2954 ha of usable data has been extracted from these studies for vegetation types classified as forest. Almost all of the FAO and RADAMBRASIL data are from one-hectare sample plots.

The parameters used for deriving the biomass estimates from the forest volume data lead to estimated biomass values substantially higher than those derived by Brown and Lugo (1992) from the FAO data and a summary of a portion of the RADAMBRASIL dataset. The difference is largely because of biomass components omitted from the Brown and Lugo estimates, including palms, vines, trees smaller than 10-cm DBH, dead biomass and below-ground biomass (Fearnside, 1992b, 1993c). Adjustments for these components are made based on available direct measurements (Fearnside, nd-a).

The total biomass is derived for each sample and the average for each ecoregion is calculated. Of the 78 forested ecoregions appearing on the IBAMA (Brazil, IBGE and IBDF, 1988) map, 44 (56%) have forest volume data available in the RADAMBRASIL or FAO datasets, and 34 (44%) do not. Fortunately, most of the ecoregions without data are of relatively minor importance from the standpoint of current greenhouse gas emissions. Of estimated biomass cleared in 1990, they total only 21.5%. For the ecoregions with no forest volume measurements, the mean biomass for the areas sampled in the same forest type (in the other states) is used as a substitute. For 5 of the 19 forest types, no measurement exists for any state. Forest types with no sample in any state represent only 1.0% of the estimated biomass cleared in 1990.

Mean biomass per hectare in each of the 78 forest types, including the values substituted as described above, are presented in Table V. It is evident that significant variation exists among states and among forest types, with pre-logging biomass loading ranging from 336 to 613 t/ha.

(Table V here)

The biomass stock in each ecoregion can be calculated by multiplying the per-hectare biomass (Table V) by the area in hectares (values from Table IV multiplied by 100 ha/km^2). Table VI gives the approximate biomass stock cleared in million t for each ecoregion in the Legal Amazon. For the region's forests as a whole, the mean biomass loading (t/ha) for pre-logging biomass (weighted by the area of each ecoregion present) is estimated at 464 t/ha (Table V). In Table VI the loading for pre-logging biomass of forests cleared in 1990 (weighted by the deforestation rate in each state) is calculated as 434 t/ha. The pre-logging biomass in the areas cleared in 1990 is 6.5% lower than the average in the region as a whole, a difference equivalent to 892 km^2 of forest clearing.

(Table VI here)

4. TRANSFORMATIONS OF GROSS CARBON STOCKS

4.1 Land Uses Replacing the Forest

Estimates of the impact of deforestation have usually assumed that all deforested land is converted to cattle pasture (the dominant land use in deforested areas in Brazilian Amazonia). Some have even assumed that the forest is replaced with bare ground. Pasture has been assumed to remain indefinitely as the replacement for forest in estimates of net greenhouse gas emissions (e.g., Fearnside, 1985, 1987), and in simulations of impact on the water cycle (e.g., Shukla *et al.*, 1990) and of the less-threatening changes in surface albedo (Dickinson and Henderson-Sellers, 1988). The results of such calculations are useful in identifying potential consequences of continued deforestation, but are unrealistic as quantitative predictions of contributions to climatic changes because the landscape that really replaces forest is not only pasture. The principal reason for using cattle pasture as the replacement vegetation has been the lack of more realistic scenarios of the evolution of the landscape after its initial conversion from forest to pasture. Here a first approximation is made using a simple first-order Markov model of transition probabilities between land-use classes (Fearnside, in press-a).

Markov matrices carry the assumption that the transfer probabilities remain unaltered over time--something for which there is no guarantee in practice. However, in most agricultural systems the tendency has been for population pressure to increase, leading to increased use intensity over time and shorter periods in secondary forest, with resulting lower average biomass for the landscape (e.g., Vermeer, 1970; UNESCO/UNEP/FAO, 1978). The assumption of constant transfer probabilities therefore is conservative from the point of view of greenhouse gas emissions. The assumption of constant transition probabilities is also optimistic because degradation of soil under pasture, combined with rainfall changes expected if the scale of deforestation should greatly expand, are likely to make low-biomass dysclimaxes, including grassy formations, the dominant land cover in a deforested Amazonia (Shukla et al., 1990; Fearnside, 1995b).

Exponentiation of the present matrix of transfer probabilities (Table VII) yields a vector representing the proportion of land in each category after establishment of equilibrium (Jeffers, 1978: 92-97). Performing these calculations indicates that the equilibrium landscape (Table VIII) would contain 0.0% forest, 4.0% farmland, 43.8% productive pasture, 5.2% degraded pasture, 2.0% secondary forest derived from farmland and 44.9% secondary forest derived from pasture. In Table VIII a weighted average is calculated of the biomass of vegetation in this equilibrium landscape, resulting in a value of 28.5 t/ha.

(Tables VII and VIII here)

The above calculations refer only to land that is cleared for agriculture and ranching. Hydroelectric development also removes forest land.

4.2. Fate of Biomass Carbon Stocks

The carbon stocks will change over a period of years to approach those in the equilibrium landscape, with the quantities in each pool increasing or decreasing at a different pace. The initial burn releases carbon immediately, while subsequent burns do so over a period of about ten years. Bacterial decomposition and termite activity also occurs largely over the first decade. Soil carbon pools change relatively quickly at the surface, but adjustments take longer for deeper pools (only carbon to 20 cm is considered in the current calculation). Charcoal (char) in the soil is a very long-term pool, considered to be permanently sequestered in the analysis.

Charcoal formed in burning is one way that carbon can be transferred to a long-term pool from which it cannot enter the atmosphere. A burn of forest being converted to cattle pasture near Manaus resulted in 2.7% of above-ground carbon being converted to charcoal (Fearnside et al., 1993). Using the mean of this and additional studies at Altamira and Manaus (Fearnside et al., nd-a,c) gives a mean of 1.9% (Table IX). This is substantially lower than the 15-23% assumed by Seiler and Crutzen (1980: 236) when they identified charcoal formation as a potentially important carbon sink (more recent calculations have used 5-10% charcoal yield: Crutzen and

Andreae, 1990: 1672). Using the observed lower rate of charcoal formation would make global carbon cycle models indicate a larger contribution of greenhouse gases from tropical deforestation than has been the case using the higher rates of carbon transfer to long-term pools (e.g., Goudriaan and Ketner, 1984).

The burning behavior of ranchers can alter the amount of carbon passing into a long-term pool as charcoal. Carbon budget calculations often assume that forest is burned only once, and that all unburned biomass subsequently decomposes (e.g., Bogdonoff et al., 1985). This is not the typical pattern in cattle pastures that dominate land use in deforested areas in the Brazilian Amazon. Ranchers reburn pastures at intervals of 2-3 years to combat invasion of inedible woody vegetation. Logs lying on the ground when these reburnings occur are often burned. Some charcoal formed in earlier burns can be expected to be combusted as well. Parameters for transformations of gross carbon stocks are given in Table IX. A typical scenario of three reburnings over a 10-year period would raise the percentage of above-ground C converted to charcoal from 1.9% to 2.4% (Tables IX and X). In addition, a small amount of elemental carbon would be formed as graphitic particulates in the smoke (not considered here); over 80% of the elemental carbon formed remains on the site as charcoal (Kuhlbusch and Crutzen, 1995). The carbon transformations over a typical 10-year sequence are shown diagrammatically in Figure 3. These and other calculations are carried out in a series of interlinked spreadsheets.

(Figure 3 and Tables IX and X here)

5. SOURCES AND SINKS OF GREENHOUSE GASES

5.1. Burning

Biomass carbon not converted to charcoal (or elemental C in the smoke) is released gradually through combustion and decay, the relative importance of each affecting the gases emitted. If an area were burned only once, 33.2% of the pre-burn above-ground carbon would be released through combustion and 64.8% through decay (the remainder enters sinks as charcoal or graphitic particulates) (Table IX). With a typical scenario of three reburnings, 42.0% would be released through combustion and 55.6% through decay. Both combustion and decay release other trace gases such as methane.

In these calculations, the burning efficiency used for the initial burn (33.2%) is the mean of three studies (Fearnside et al., 1993, nd-a,b), adjusted for the effect of removal of trunks by logging (Fearnside, nd-b). The burning studies used found, respectively, efficiencies of 27.6% in a 1984 burn near Manaus, Amazonas, 42.0% as the mean of three 1986 burns near Altamira, Pará, and 28.3% in a 1990 burn near Manaus. Kauffman et al. (1995) have recently found higher burning efficiencies: 51.5% in a 1990 burn at Jacundá, Pará, 51.3% in a 1991 burn at Marabá, Pará, 40.5% in a 1992 burn at Santa Barbara, Rondônia, and 56.1% in a 1992 burn at Jamurí, Rondônia.

Parameters for carbon emissions (CO_2, CH_4 and CO) from the different burning and decay transformations of biomass are given in Table X. Two sets of parameters are given: a "low trace gas" and a "high trace gas" scenario, reflecting the range of values appearing in the literature for trace gas releases from such sources as termites and flaming and smoldering burns. Carbon emissions as CO_2, CH_4 and CO are diagrammed in Figure 4 with parameters for the low trace gas scenario. The low and high trace gas scenarios reflect the range of values for trace gas emissions only, not the level of uncertainty for factors affecting the amount of material that burns or decays, such as forest biomass, deforestation rate and burning efficiency. Parameters for other sources of greenhouse gases from land-use change are given in Table XI, and trace gas release parameters are given in Table XII.

(Figure 4 and Tables XI and XII here)

The amount of methane released is heavily dependent on the ratio of smoldering to flaming combustion; smoldering releases substantially more CH_4. Aircraft sampling over fires (mostly from virgin forest clearing) indicates that a substantial fraction of combustion is in smoldering form (Andreae et al., 1988). Logs consumed by reburning of cattle pastures are virtually all burned through smoldering rather than flaming combustion (personal observation).

Carbon monoxide (CO) is also produced by burning. This gas contributes indirectly to the greenhouse effect by impeding natural cleansing processes in the atmosphere that remove a number of greenhouse gases, including methane. Carbon monoxide removes hydroxyl radicals (OH), which react with CH_4 and other gases.

Burning also releases some nitrous oxide (N_2O), which contributes both to the greenhouse effect and to the degradation of stratospheric ozone. A sampling artifact has made measurements prior to 1989 unusable (Muzio and Kramlich, 1988). Estimates after discovery of the artifact indicate N_2O emissions from biomass burning are substantially lower than had previously been thought (Crutzen and Andreae, 1990). Parameters used in the present estimate (Table XII) are unaffected by the artifact.

5.2. Removal of Intact Forest Sources and Sinks

Deforestation makes an additional contribution to methane by removing a CH_4 sink in the soil of intact forest (Table XII). Removal of intact forest sources and sinks also affect the contribution of deforestation to a variety of compounds of nitrogen and oxygen (NO_x) and to non-methane hydrocarbons

(NMHC), especially isoprenes. Effects of removing intact forest sources are included in the parameters for trace gases (Table XII). No forest sink is explicitly included for N_2O because the emission values used for this gas represent the net difference between forest and pasture emissions.

In the case of NMHC, the net effect of deforestation is to decrease the source strength over the 100-year period used in the current calculation. The magnitude of the effect of this reduction on global warming cannot be calculated yet. Indirect effects of trace gases were included in the 1990 IPCC scientific assessment of climate change (J.T. Houghton et al., 1990) but were dropped in the 1992 IPCC supplementary report pending resolution of disagreements over the magnitude of the effects (J.T. Houghton et al., 1992). Some of the indirect effects were restored in the 1994 report in the case of CH_4, raising its 100-year time horizon global warming potential from 11 to 24.5 as compared to CO_2 on a mass basis (Albritton et al., 1995: 222), making 1 t of CH_4 carbon equivalent to 8.9 t of CO_2 carbon [Note these values are expected to decrease to 21 and 7.6, respectively, in the 1995 IPCC report]. No indirect effects are yet agreed upon for NO_x and NMHC (as well as CO), which continue to be considered as having zero global warming potential (Albritton et al., 1995: 222).

5.3. Soil Carbon

Release of soil carbon would be expected when forest is converted to pasture because soil temperatures increase when forest cover is removed, thus shifting the balance between organic carbon formation and degradation to a lower equilibrium level (Cunningham, 1963; Nye and Greenland, 1960). A number of studies have found lower carbon stocks under pasture than forest (reviewed in Fearnside, 1980). For the same reason, naturally occurring tropical grasslands also have much smaller soil carbon stocks per hectare than do forests (Post et al., 1982). Lugo et al. (1986), however, have found increases in carbon storage in pasture soils in Puerto Rico, especially in drier sites, and suggest that tropical pastures may be a carbon sink. The present study treats soils as a source of carbon when forests are converted to pasture. All carbon released from soils is assumed to be in the form of CO_2.

Soil carbon in pasture is taken to be that in a profile equivalent to what is compacted from a 20-cm profile in the forest. Parameters used in deriving soil carbon changes are given in Table XIII. The layer compacted from the top 20 cm of forest soil releases 3.92 t/ha of carbon (the value used in the current calculations).

(Table XIII here)

The 3.92 t/ha release from the top 20 cm of soil represents 38% of the pre-conversion carbon present in this layer. This is higher than the 20% of pre-conversion carbon in the top 40 cm of soil that Detwiler (1986) concluded is released, on average, from conversion to pasture. The difference is not so great as it might seem: since carbon release is greatest nearest the surface, considering soil to 40 cm would thereby reduce the percentage released. One factor acting to compensate for any overestimation possibly caused by using a higher percentage of soil carbon release in the present study is the low bias introduced by having considered only the top 20 cm.

If soil to one-m depth were considered (the usual practice), and the same 38% of pre-conversion carbon were assumed to be released, then the release would be increased to 9.33 t/ha (Table XIII). The calculation to one-m depth considers that the top 20 cm of soil contains 42% of the carbon in a one-m profile (based on samples near Manaus: Fearnside, 1987). Brown and Lugo (1982: 183) have used a similar relationship to estimate carbon stocks in Thailand to a depth of one m from samples of the top 20 cm, considering 45% of the carbon in a one-m profile to be located in the top 20 cm.

Soil carbon release may be substantially higher than the values used here. Nepstad et al. (1994) have found carbon stocks 16 t/ha lower in the top one m of soil under degraded pasture as compared to intact forest, implying a carbon emission from soil about twice the values used. The combined effect of adopting these higher values and extending consideration from the top 20 cm to the top meter of soil would be to increase soil emissions by a factor of four, resulting in an additional net committed emission of about 30 X 10^6 t of CO_2-equivalent carbon from the area cleared in 1990.

On the other hand, some studies have indicated less carbon loss than the value adopted here. Desjardins et al. (1994) found a net loss of 2.3 t/ha in the top 20 cm of soil in Pará, about 40% less than the value used here. The authors of the study believed that carbon loss in the 10-year-old pasture was relatively low because it had not been actively used "for a few years" (Desjardins et al., 1994: 112). Cerri et al. (1991: 254) found that 12 t/ha were lost from the top 20 cm during the first year, but that 8-year-old pasture had recovered the soil carbon stocks of forest and increased the stock in the top 20 cm to a level 6 t/ha above that in the forest soil. They attributed the strong recovery to "a rather exceptional management" in an "almost ideal well managed pasture" at an agricultural experiment station near Manaus (Cerri et al., 1991: 255). The studies indicating only slight carbon loss or a carbon gain do not include correction for soil compaction under pasture, making them underestimate the carbon loss that occurs from the layer of soil compacted from a given layer of the original forest soil (Fearnside, 1985, 1987; Veldkamp, 1993).

Soil below one-m depth may also be releasing significant amounts of carbon in deforested areas. Nepstad et al. (1994) have found carbon stocks at 1-8 m depth exceeding those in the top meter, and isotopic data indicate that this deeper pool experiences significant turnover, which is expected to result in carbon releases as the elimination of deep roots removes the source of replenishment for the deep soil carbon pool. Major adjustments of soil carbon inventory, including pools in the deeper soil layers, occur within the first decade after deforestation (Trumbore et al., 1995).

The present analyis considers all loss of carbon inventory from the top 20 cm of forest soil to be emissions, whether or not the losses occur through release of CO_2 directly to the atmosphere or by leaching to deeper soil layers and from there to groundwater and river outflow. The atmospheric effect of loss to groundwater is probably almost the same as if the carbon had been released directly. Since carbon in groundwater is in dissolved rather than particulate form, it would not enter ocean sediments and would remain exposed to oxidation after reaching the sea. Half of the carbon entering the Amazon River is oxidized before it reaches the ocean (Richey et al., 1980: 1350). A modest amount of carbon is undoubtedly lost through erosion as particulates and survives transport to long-term pools in ocean sediments (not considered in the current analysis).

5.4. Termites and Decay

A lively controversy surrounds the question of how much methane is produced by termites (Collins and Wood, 1984; Fraser et al., 1986; Rasmussen and Khalil, 1983; Zimmerman et al., 1982, 1984). This stems from differing estimates of the number of termites, the amount of wood consumed per termite, and the methane emission per gram of wood consumed. No measurement exists of the percentage of felled biomass that is ingested by termites in Amazonian clearings. Termite populations increase to a peak approximately 5-6 years after clearing, and subsequently decline as the available wood disappears (A.G. Bandeira, personal communication, 1990). It is assumed that none of the below-ground wood is ingested by termites: a conservative assumption given that termite species that eat buried wood are known to occur (Bandeira and Macambira, 1988) and termites consume underground biomass in other regions, such as Africa (e.g. Wood et al., 1977).

The termite emissions are limited by the ability of the termite populations to expand to consume the large amount of dead wood biomass that becomes available to them after deforestation. Both in the forest and in clearings, the inability of the observed populations to ingest the quantity of wood available makes the amount of wood biomass consumed independent of the amount of wood present. The calculations used here (Martius et al., nd) are based on the one available measurement of wood consumption, which is for the termite Nasutitermes macrocephalus (a wood-feeding species in the Amazonian várzea): 49 mg of wood dry weight consumption per gram of termite biomass per day (Martius, 1989: 228).

Both the high and low trace gas scenarios use the average emission rate for wood-feeders (Martius, et al., 1993) applied to the total termite biomass of wood-, soil- and leaf-feeders. This emission of 3.0±1.3 μg/hour is equivalent to 0.0022 tons of carbon released as methane per ton of carbon consumed (considering 50% carbon content of wood). This is virtually identical to the value obtained by Seiler et al. (1984) for termites in Africa. It is lower by a factor of four than the 0.0079 t methane C released/t wood C consumed estimated for Amazonian termites by Goreau and de Mello (1987). However, the lower value (Martius, et al., 1993) is believed to be more reliable, as the higher value was based on monitoring a single nest for only two days, whereas the value used here is based on monitoring 15 nests for two years.

5.5. Cattle and Pasture

Methane is produced in the rumens of cattle that occupy pastures in deforested areas. The portion of the deforested area considered to be maintained under pasture is that derived from the equilibrium landscape (Tables VII and VIII). Parameters used to derive methane emissions from cattle are included in Table XI.

Pasture soils in Amazonia emit N_2O in quantities substantially higher than forest soils when measurements are made over a full annual cycle (Luizão et al., 1989). Most emissions are in the wet season, and are not reflected in measurements restricted to the dry season (e.g. Goreau and de Mello, 1987). Unlike emissions from the initial burning, conversion of a given hectare to pasture does not result in a one-time release of this greenhouse gas, but rather a continuous additional flux at this rate for as long as the area is maintained under this land use (the assumption in the present calculation). However, Keller et al. (1993) have found that N_2O emissions from pasture soil declines with pasture age in Costa Rica, falling below emission levels from forest soils after 10 years.

One factor not included in the calculation is production of trace gases by reburning of pasture and secondary forest. Combustion of logs remaining from the original forest is included. Burning of the biomass of the pasture itself and of secondary forest does not contribute to net release of carbon dioxide, as the same amount of carbon is reabsorbed when the vegetation regrows. However, CH_4, CO, N_2O and NO_x do increase as a result of reburnings as these gases do not enter photosynthetic reactions. Methane degrades to CO_2 after an average of 14.5 years (Albritton et al., 1995: 222), and CO degrades after a few months (Thompson and Cicerone, 1986: 10,857), after which the carbon can return to the vegetation. The trace gas inputs of reburning the replacement vegetation represent one of several factors not included in the current calculation of net committed emissions, but which are included in calculations of the annual balance of emissions (Fearnside, in press-b). Burning of *cerrado* and other savanna vegetation without clearing of trees is a source of trace gas emissions in the annual balance, but does not contribute to net committed emissions (because only the fate of the cleared area is followed).

5.6. Hydroelectric Dams

Because no new reservoirs were filled in 1990, the calculations presented above consider only emissions from conversion of natural forest vegetation to a landscape dominated by cattle pasture--the dominant trend in Brazilian Amazonia today. Hydroelectric dams in rainforest areas release greenhouse gases both by decomposition of dead forest left standing in the reservoirs and by the continuing release of methane from flooded areas (especially in portions that are alternately dried and flooded).

Although hydroelectric dams are commonly believed to have no impact on the greenhouse effect, in contrast to fossil fuel use, the validity of this conclusion depends heavily on the biomass of the vegetation in the flooded areas and on the power output of the dams. In Amazonia, dams are sometimes worse than petroleum from the point of view of greenhouse gas emissions. The worst case is Balbina Dam, which was closed in 1987. Located on relatively flat terrain, Balbina's shallow 3147 km^2 reservoir can generate only enough power to deliver annually an average of 109 megawatts to Manaus (Fearnside, 1989a). The biomass of the flooded forest is now decomposing, releasing its carbon to the atmosphere. Methane is also released from decay of biomass under the anoxic conditions at the bottom of the reservoir. Generating the same energy from petroleum would take 250 years to equal the carbon release from flooding the Balbina reservoir (based on Junk and Nunes de Mello, 1987; see Fearnside, 1989a). However, most of the carbon release from reservoirs takes place in the first decade, which increases the importance of these emissions relative to those from fossil fuels when calculations include time horizons and/or weighting of emissions for time preference as by discounting. In 1990, Balbina was releasing twenty times more CO_2-equivalent carbon than would have been produced by generating the same power from fossil fuels (Fearnside, 1995c).

Calculating emissions for hydroelectric dams requires estimating vertical distribution of the biomass in order to calculate releases occurring above the water, in the seasonally-inundated zone, and underwater in the surface and anoxic water portions of the reservoir. Transfers from the above-water to the underwater categories occur as branches and trunks fall. Assumptions about decay rates and paths allow estimation of emissions of CO_2 and CH_4 from forest biomass. To these emissions are added CH_4 releases from decay of macrophytes and of organic matter entering the reservoir from the river. The emission in 1990 from the approximately 5500 km^2 of reservoirs in the region was 38 X 10^6 t of CO_2 gas and

0.22 X 10^6 t of CH_4 gas (Fearnside, 1995c). In 1990, no new reservoirs were filled in the Legal Amazon.

Amazonian várzea (white water floodplain) has been identified as one of the world's major sources of atmospheric methane (Mooney et al., 1987). Várzea occupies about 2% of the five X 10^6 km^2 Legal Amazon, the same percentage that would be flooded if all of the reservoirs planned for the region are created. A total of 100,000 km^2 would be flooded (Brazil, ELETROBRÁS, 1987: 150), or about 20 times the present reservoir area. Virtually all planned hydroelectric dams are in the forested portion of the region--and the reservoirs would flood approximately 2.5% of this portion of the region. Were these reservoirs to contribute an output of methane per hectare on the same order as that produced by the várzea, they would together represent a significant contribution to the greenhouse effect. The annual emission of methane to the atmosphere from the várzea has been calculated by Devol et al. (1990) to be 5.1 X 10^6 t CH_4/year. Like biogenic release of N_2O, this would be a permanent addition to greenhouse gas sources, rather than a one-time input. Unfortunately, CH_4 emission measurements from Amazonian reservoirs do not yet exist, making measurements in várzea lakes the best available surrogate.

6. NET COMMITTED EMISSIONS

The quantities of gases released by each source and absorbed by each sink in the 13.8 X 10^3 km^2 of forest and 5 X 10^3 km^2 of cerrado cleared in 1990 are given in Table XIV for the low trace gas scenario. Table XV presents the corresponding results for the high trace gas scenario. Although the emissions of CO_2 dwarf the absolute quantities of the other gases, the greater greenhouse impact per ton of the latter gives them a significant role in deforestation's contribution to global warming.

(Tables XIV and XV here)

I have converted my estimated emissions of trace gases to CO_2 equivalents (Table XVI). The conversion uses the global warming potentials adopted by the Intergovernmental Panel for Climate Change (IPCC) in its 1994 report (Albritton et al., 1995: 222). These express the impact on global warming of an immediate emission of one ton of each gas relative to emitting one ton of CO_2 gas, considering a 100-year time horizon without discounting. The exclusion of a number of indirect effects, the long time horizon and the lack of discounting all reduce the weight given to CH_4 and CO relative to CO_2, thereby reducing the calculated impact of tropical deforestation relative to fossil fuel combustion (Fearnside, 1992a).

(Table XVI here)

Using this conservative methodology for expressing trace gas impact, the CO_2-equivalent carbon from trace gases represents 5% and 9% of the total in the low and high trace gas scenarios, respectively. The total contribution of 1990 clearing in forest and cerrado was 274-285 X 10^6 t of CO_2-equivalent carbon (Table XVI). In addition to this, logging in 1990 emitted 61 X 10^6 t CO_2-equivalent C (Fearnside, nd-b). As this was calculated assuming a constant logging harvest at the 1988 official rate (24.6 X 10^6 m^3/year), it reflects net committed emissions from logging. Adding this to the total from forest clearing raises the net committed emission for 1990 land-use change in the Brazilian Legal Amazon to 335-346 X 10^6 t CO_2-equivalent carbon. This represents roughly 5% of the total global emissions from deforestation and fossil fuel sources, indicating the high impact of deforestation. At the same time, it makes clear the fact that reducing or halting deforestation is not enough to avoid the most damaging consequences of global warming, and that use of fossil fuels must also be substantially reduced.

* NOTE

(*) Some inconsistency remains in the definition of original forest area used here (Tables III and IV), and that used in the deforestation estimate (Tables I and II). The deforestation estimate used a line between forest and nonforest drawn by INPE from LANDSAT-TM 1:250,000 scale images with some reference to the RADAMBRASIL vegetation maps (but without a list of vegetation types classified as forest and nonforest). The area so defined has not yet been measured by INPE, but a compilation by map sheet (using IBGE 1:250,000 scale maps as a geographical base) was made of the approximate proportions of forest and nonforest in each sheet. The total from this compilation is 4.0 X 10^6 km^2, lower than the 4.3 X 10^6 km^2 measured from the IBGE/IBDF 1:5,000,000 scale map.

The "present" vegetation is also inconsistent: the IBGE/IBDF mapping totals 3.7 X 10^6 km^2 of forest (circa 1988) (Table IV), whereas the original forest area from the same map, less the area deforested by 1988 (Table I), yields a total of 3.9 X 10^6 km^2.

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FIGURE LEGENDS

Fig. 1. Brazil's Legal Amazon region, with locations mentioned in the text.

Fig. 2. Forest and nonforest in the Brazilian Legal Amazon (Source: Fearnside and Ferraz, 1995).

Fig. 3. Carbon transformations through a typical 10-year sequence of clearing, burning and reburning (updated from: Fearnside, 1991).

Fig. 4. Partioning of carbon between type of release and emitted gas (Low trace gas scenario) (updated from: Fearnside, 1991).

TABLE I: EXTENT OF DEFORESTATION IN THE BRAZILIAN LEGAL AMAZON[(a)]

Political unit	Original forest area ($km^2 \times 10^3$)	Deforested area ($km^2 \times 10^3$)					Deforested area (% of original forest area)				
		Jan. 1978	Apr. 1988	Aug. 1989	Aug. 1990	Aug. 1991	Jan. 1978	Apr. 1988	Aug. 1989	Aug. 1990	Aug. 1991
Acre	152	2.6	8.9	9.8	10.3	10.7	1.7	5.8	6.4	6.8	7.0
Amapá	115	0.2	0.9	1.0	1.3	1.7	0.2	0.8	0.9	1.1	1.5
Amazonas	1,481	2.3	18.0	19.3	19.8	20.8	0.2	1.2	1.3	1.3	1.4
Maranhão	143	65.9[(b)]	90.8[(b)]	92.3[(b)]	93.4[(b)]	94.1[(b)]	46.1	63.5	64.5	65.3	65.8
Mato Grosso	528	26.5	71.5	79.6	83.6	86.5	5.0	13.5	15.1	15.8	16.4
Pará	1,139	61.7[(b)]	129.6[(b)]	137.3[(b)]	142.2[(b)]	146.0[(b)]	5.4	11.4	12.1	12.5	12.8
Rondônia	215	6.3	29.6	31.4	33.1	34.2	2.9	13.8	14.6	15.4	15.9
Roraima	164	0.2	2.8	3.6	3.8	4.2	0.1	1.7	2.2	2.3	2.6
Tocantins	59	4.2	21.6	22.3	22.9	23.4	7.1	36.7	37.9	38.9	39.7
Legal Amazon	3,996	169.9	373.9	396.6	410.4	421.6	4.3	9.4	9.9	10.3	10.5

	FOREST FLOODED BY HYDROELECTRIC DAMS									
Legal Amazon	0.1	4.4	5.5	5.5	5.5	0.0	0.1	0.1	0.1	0.1
	DEFORESTATION FROM ALL SOURCES									
Legal Amazon	169.9	378.3	402.1	416.0	427.1	4.3	9.5	10.1	10.4	10.7

(a) Sources: Fearnside, 1993a,b

(b) Maranhão values include 57.8 X 10^3 km^2, and Pará values include 39.8 X 10^3 km^2, of "old" (approximately pre-1970) deforestation now largely under secondary forest.

TABLE II: RATE OF DEFORESTATION IN THE BRAZILIAN LEGAL AMAZON[a]

Political unit	Deforestation rate (km^2 X 10^3/year)			
	1978-1988	1988-1989	1989-1990	1990-1991
	DEFORESTATION EXCLUSIVE OF HYDROELECTRIC DAMS			
Acre	0.6	0.6	0.6	0.4
Amapá	0.1	0.2	0.3	0.4
Amazonas	1.6	1.3	0.5	1.0
Maranhão	2.5	1.4	1.1	0.7
Mato Grosso	4.5	6.0	4.0	2.8
Pará	6.8	5.8	4.9	3.8
Rondônia	2.1	1.4	1.7	1.1
Roraima	0.2	0.7	0.2	0.4
Tocantins	1.6	0.7	0.6	0.4
Legal Amazon	20.0	18.1	13.8	11.1
	FOREST FLOODED BY HYDROELECTRIC DAMS			

Legal Amazon	0.4	1.1	0.0	0.0
DEFORESTATION FROM ALL SOURCES				
Legal Amazon	20.4	19.2	13.8	11.1

(a) Sources: Fearnside, 1993a,b

TABLE III: VEGETATION TYPES IN THE BRAZILIAN LEGAL AMAZON[a]

Category	Code	Group	Subgroup	Class
Dense Forest	Da-0	Ombrophilous forest	Dense forest	Alluvial Amazonian
	Db-0	Ombrophilous forest	Dense forest	Lowland Amazonian
	Dm-0	Ombrophilous forest	Dense forest	Montane Amazonian
	Ds-0	Ombrophilous forest	Dense forest	Submontane Amazonian
Non-dense forest	Aa-0	Ombrophilous forest	Open	Alluvial
	Ab-0	Ombrophilous forest	Open	Lowland
	As-0	Ombrophilous forest	Open	Submontane
	Cs-0	Seasonal forest	Deciduous	Submontane
	Fa-0	Seasonal forest	Semideciduous	Alluvial
	Fs-0	Seasonal forest	Semideciduous	Submontane
	La-0	Woody oligotrophic vegetation of swampy and sandy areas		Open arboreous
	Ld-0	Woody oligotrophic vegetation of swampy and sandy areas		Dense arboreous
	Lg-0	Woody oligotrophic vegetation of swampy and sandy areas		Grassy-woody
	LO-0	Areas of ecological tension and contact		Woody oligotrophic vegetation of swampy and sandy areas--ombrophilous forest
	ON-0	Areas of ecological tension and contact		Ombrophilous forest--seasonal forest
	Pf-0	Areas of pioneer formations		Fluvio-marine influence
	SM-0	Areas of ecological tension and contact		Savanna--dense ombrophilous forest
	SN-0	Areas of ecological tension and contact		Savanna--seasonal forest
	SO-0	Areas of ecological tension and contact		Savanna--ombrophilous forest
Non-forest	Pa-0	Areas of pioneer formations		Fluvial influence
	rm-0	Ecological refugium	High altitude	Montane
	Sa-0	Savanna	Cerrado	Open arboreous
	Sd-0	Savanna	Cerrado	Dense arboreous
	Sg-0	Savanna	Cerrado	Grassy-woody
	Sp-0	Savanna	Cerrado	Parkland
	ST-0	Areas of ecological tension and contact		Savanna--steppe-like savanna
	Td-3	Steppe-like savanna	Roraima grasslands	Dense arboreous
	Tp-3	Steppe-like savanna	Roraima grasslands	Parkland

(a) Source: Brazil, IBGE and IBDF, 1988.

TABLE IV: AREA OF NATURAL VEGETATION PRESENT IN THE BRAZILIAN LEGAL AMAZON[(a)]

Category	Code	Acre	Amapá	Amazonas	Maranhão	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total present
Dense forest	Da-0		9,011	164,876			76,570	2,704	3,326	2,610	259,097
	Db-0	16,408	2,184	615,203	22,586		164,091	2,066	10,248		832,786
	Dm-0		113	10,181			3,418		20,661		34,373
	Ds-0	518	99,220	178,103	1,988	23,154	413,345	14,607	83,692	3,055	817,682
	Subtotal	16,926	110,528	968,363	24,574	23,154	657,424	19,377	117,927	5,665	1,943,938
Non-dense forest	Aa-0	10,591		65,748			805	2,273			79,417
	Ab-0	114,380		211,052				41,064			366,496
	As-0			37,555		124,620	286,271	77,794	8,430	1,216	535,886
	Cs-0				3,666	736	5,386			115	9,903
	Fa-0					3,554					3,554
	Fs-0					24,317		7,718	1,041	1,328	34,404
	La-0			14,979					970		15,949
	Ld-0			37,405					10,967		48,372
	Lg-0			9,663					9,767		19,430
	LO-0			172,607					30,184		202,791
	ON-0					168,069	2,991	4,801	3,045		178,906
	Pf-0		1,823		2,089		3,894				7,806
	SM-0				384						384
	SN-0			1,082	6,570	142,778	27,812	4,781	904	14,465	198,392
	SO-0		4,226	27,350		22,124	59,734	21,932	4,286	6,551	146,203
	Subtotal	124,971	6,049	577,441	12,709	486,198	386,893	160,363	69,594	23,675	1,847,893
	Subtotal	141,897	116,577	1,545,804	37,283	509,352	1,044,317	179,740	187,521	29,340	3,791,831

	all forests										
Non-	Pa-0		15,157	12,778	2,517	14,738	27,162	8,690			81,042
forest	rm-0								390		390
	Sa-0			1,531	55,758	167,534	5,686	11,028		102,445	343,982
	Sd-0				15,771	10,840	1,274			2,234	30,119
	Sg-0					10,490	5,057		15,481	7,113	38,141
	Sp-0		10,038	5,556	26,980	64,085	12,393	2,664	8,969	48,962	179,647
	ST-0					6,599					6,599
	Td-3								1,550		1,550
	Tp-3								10,671		10,671
	Subtotal	0	25,195	19,865	101,026	274,286	51,572	22,382	37,061	160,754	692,141
	Total	141,897	141,772	1,565,669	138,309	783,638	1,095,889	202,122	224,582	190,094	4,483,972

(a) Areas in km^2 measured from 1:5,000,000 vegetation map (Brazil, IBGE and IBDF, 1988).

These areas do not reflect losses due to recent deforestation.

TABLE V: FOREST BIOMASS PER HECTARE: MEANS BY ECOREGION, VEGETATION TYPE AND STATE (t/ha)[a]

Category	Code	Acre	Amapá	Amazonas	Maranhão	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Mean in sampled plots	Area-weighted mean
Dense forest	Da-0		471	513			412	310	419	500	498	478
	Db-0	438	583	495	458		585	546	417		551	510
	Dm-0		441	344			441		448		440	417
	Ds-0	391	613	478	464	402	518	464	429	111	430	506
	Dense forests	437	601	493	459	402	522	452	431	290	519	502
Non-dense forest	Aa-0	425		435			536	431			430	434
	Ab-0	455		466				403			455	456
	As-0			507		426	361	378	376	376	374	389
	Cs-0				384	384	384			384	384	384
	Fa-0					370					370	370
	Fs-0					403		472	424	424	423	420
	La-0			465					465			435
	Ld-0			437					437			435
	Lg-0			437					437			435
	LO-0			500					437		499	490
	ON-0					383	401	547	409		401	389
	Pf-0		437		464		437					435
	SM-0				437							435
	SN-0			409	385	383	479	385	336	385	385	397
	SO-0		404	582		360	410	404	404	404	402	433
Non-dense		453	414	478	399	394	379	399	425	392	435	423

forests											
All forests	451	591	488	438	394	469	404	429	372	500	464

(a) Values in italics are for ecoregions where no sample exists: values are based on the mean in sampled plots for the same vegetation type in other states. Source: Fearnside, nd-a.

TABLE VI: APPROXIMATE BIOMASS CLEARED IN 1990 IN EACH ECOREGION IN THE BRAZILIAN LEGAL AMAZON (10^3 t/year)

Cate-gory	Code	Acre	Amapá	Amazonas	Maranhão	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total
Dense	Da-0		944	2,924			15,013	733	125	2,600	22,339
forest	Db-0	2,846	293	10,492	29,196		44,014	1,106	384		88,331
	Dm-0		11	77			717		807		1,613
	Ds-0	80	13,993	2,981	2,978	7,391	99,957	6,400	3,015	689	137,484
	subtotal	2,926	15,242	16,474	32,175	7,391	159,702	8,238	4,331	3,288	249,767
Non-	Aa-0	1,780		1,020			205	961			3,966
dense	Ab-0	20,448		3,472				16,183			40,103
forest	As-0			669		42,163	49,222	27,044	284	931	120,313
	Cs-0				4,551	225	984			90	5,850
	Fa-0					1,044					1,044
	Fs-0					7,786		3,576	40	777	12,178
	La-0			239					40		279
	Ld-0			577					411		989
	Lg-0			151					383		534
	LO-0			2,815					1,121		3,936
	ON-0					51,195	570	2,574	112		54,451
	Pf-0		28		3,129		810				3,967
	SM-0				543						543
	SN-0			16	8,173	42,641	6,337	1,805	27	11,348	70,347
	SO-0		319	569		6,334	11,647	7,506	155	5,395	31,926
	Subtotal	22,228	347	9,528	16,396	151,387	69,778	59,648	2,573	18,541	350,426
	Subtotal	25,155	15,589	26,002	48,571	158,779	229,480	67,886	6,904	21,829	600,193

	all forests										
Average biomass/ ha cleared	Dense forests	437	601	494	459	402	522	453	431	288	500
	non-dense forests	453	407	478	399	394	379	399	425	391	397
	All forests	451	595	488	437	394	468	405	429	371	434

TABLE VII: ANNUAL PROBABILITIES OF TRANSFER

Initial state	Subsequent state: Regenerated Forest	Farmland	Productive pasture	Degraded pasture	Secondary forest from farmland	Secondary forest from pasture
Regenerated Forest	0	0.347	0.653	0	0	0
Farmland	0	0.450	0.468	0	0.082	0
Productive pasture	0	0	0.849	0.008	0	0.143
Degraded pasture	0	0	0.007	0.926	0	0.067
Secondary forest from farmland	5.17×10^{-10}	0.065	0.128	0	0.807	0
Secondary forest from pasture	7.16×10^{-8}	0.061	0.101	0	0	0.838

TABLE VII: ANNUAL PROBABILITIES OF TRANSFER

Initial state	Subsequent state: Regenerated Forest	Farmland	Productive pasture	Degraded pasture	Secondary forest from farmland	Secondary forest from pasture
Regenerated Forest	0	0.347	0.653	0	0	0
Farmland	0	0.450	0.468	0	0.082	0
Productive pasture	0	0	0.849	0.008	0	0.143
Degraded pasture	0	0	0.007	0.926	0	0.067
Secondary forest from farmland	5.17×10^{-10}	0.065	0.128	0	0.807	0
Secondary forest from pasture	7.16×10^{-8}	0.061	0.101	0	0	0.838

TABLE VIII: REPLACEMENT VEGETATION WEIGHTED BIOMASS CALCULATION AT EQUILIBRIUM

Category	Equilibrium proportion	Biomass (t/ha total)	Residence time (years)	Biomass source
Forest	0.000	464	0.0	(a)
Farmland	0.040	0.7	0.9	(b)
Productive Pasture	0.438	10.7	4.2	(c)
Degraded pasture	0.052	8.0	9.1	(d)
Secondary forest from agriculture	0.020	35.6	3.2	(d)
Secondary forest from pasture	0.449	50.5	3.9	(d)
Weighted mean:		28.5		

(a)Secondary forest is assumed to be equivalent to original forest from the standpoint of biomass after 100 years. Saldarriaga _et al_. (1986: 96) calculated recovery in 144-189 years in Venezuela. Original forest biomass from Fearnside (nd-a).
(b) Guess: above-ground biomass=0.5 t/ha; root/shoot ratio=0.3.
(c) Fearnside _et al_., nd-b, see Fearnside, 1989b.
(d) Calculated from the residence time and growth rate (Fearnside and Guimaraes, 1996).

TABLE IX: PARAMETERS FOR TRANSFORMATIONS OF CARBON STOCKS

Parameter	Value	Units	Source	Comment
Total biomass	407.0	t/ha dry weight	Fearnside, nd-b	Weighted mean for areas being cleared in 1990 (after logging).
Carbon content of forest biomass	0.50	fraction of dry weight	Measured at Manaus by Fearnside *et al*., 1993	Many authors use a value of 0.45, but without reference to experimental data for its origin. Brown and Lugo (1984) use a value of 0.50.
Above ground fraction	0.759		Calculated from Fearnside, nd-b	Total above-ground biomass/total biomass of 1990 areas at time of clearing.
Burning efficiency in initial burn	0.332	fraction of C released	Fearnside *et al*., 1993, nd-a,b adjusted for logging by Fearnside, nd-b	For areas cleared after preparatory logging.
Char C fraction in initial burn	0.019		Fearnside *et al*., 1993, nd-a,b	Average of two studies near Manaus, Amazonas and one in Altamira, Pará.
Fraction of char on biomass following initial burn	0.89		Fearnside *et al*., nd-a	Near Altamira, Pará.
Exposed to soil char C transfer fraction during first interval	0.3		Guess	First interval = 5 years.
Fraction surviving decay in first interval	0.400		Calculated from Uhl and Saldarriaga, nd and Buschbacher, 1984[(a)]	
Burning efficiency in first reburn	0.201	fraction of C released	Fearnside, *et al*., nd-d; Barbosa, 1994	Burns of secondary forest and pasture in Apiaú, Roraima
Fraction converted to char in first reburn	0.010		Fearnside, *et al*., nd-d; Barbosa, 1994	Burns in Apiaú, Roraima (NB: includes charcoal from secondary forest, but not secondary forest biomass)
Char C combustion fraction in first reburn	0		Assumed zero because char conversion value is net	
Fraction surviving decay in second interval	0.543		Calculated from Uhl and Saldarriaga, nd[(a)]	Second interval = 3 years
Burning efficiency in second reburn	0.201	fraction of C released	Assumed equal to first reburn	
Fraction of C converted to char in second reburn	0.010		Assumed equal to first reburn	

Fraction of char on biomass after first reburn	0.89		Assumed equal to initial burn	
Exposed to soil char C transfer fraction during second interval	0.3		Guess	
Char C combusted fraction in second reburn	0		Assumed zero because char conversion value is net	
Fraction of char on biomass after second reburn	0.89		Assumed equal to initial burn	
Exposed to soil char C transfer fraction during third interval	0.3		Guess	
Fraction surviving decay in third interval	0.767		Calculated from Uhl and Saldarriaga, nd.	Third interval = 3 years
Burning efficiency in third reburn	0.201	fraction of wood C released	Assumed equal to first reburn	
Fraction of C converted to char in third reburn	0.010		Assumed equal to first reburn	
Char C combustion fraction in third reburn	0		Assumed zero because char conversion value is net	
Soil C release from top 20 cm	3.92	t/ha	Fearnside, 1985, 1987	
Replacement vegetation biomass	28.5	t/ha	Table VIII.	Weighted average for equilibrium landscape
Carbon content of replacement vegetation biomass	0.45	fraction of dry weight	Based on measurements at Altamira by Guimarães, 1993.	

(a) See Fearnside, in press-b

TABLE X: PARAMETERS FOR CARBON EMISSIONS

Scenario	Component	Transformation	Value (t C released in this form / t C present in component)	t gas released/t fuel burned	Basis and reference
Both high and low trace gas scenarios	Above-ground biomass carbon	Combustion release	0.4203		Calculated from parameters in Table IX and Figure 3
		Decay release	0.5561		Calculated from parameters in Table IX and Figure 3
		Charcoal carbon formation (initial+subsequent burns)	0.0237		Calculated from parameters in Table IX and Figure 3
	Carbon released through combustion	Initial burn	0.7905		Calculated from parameters in Table IX and Figure 3
		Reburns	0.2095		Calculated from parameters in Table IX and Figure 3
		Combustion release of below-ground biomass	0		Assumption
	Carbon released through decay	Decay release through termites (above ground)	0.0297		Martius <u>et al</u>., nd (average for first 10 years for original forest biomass; emission calculations done with a different proportion for each year)
		Decay release through other decay (above ground)	0.9703		One minus decay release through termites
		Decay release of below-ground biomass	1		Assumption
		Decay release through termites (below ground)	0		Assumption (unrealistically low)
		Decay release through other decay	1		Assumption (unrealistically high)

		(below ground)			
Low trace gas scenario	Carbon released by combustion in initial burn	CH_4 carbon	0.0078	0.005	Kaufman et al., 1990 from Ward, 1986[a]
		CO_2 carbon	0.8779	1.55	Kaufman et al., 1990 from Ward, 1986[a]
		CO carbon	0.1068	0.12	Kaufman et al., 1990 from Ward, 1986[a]
	Carbon released by combustion in reburns	CH_4 carbon	0.0109	0.007	Kaufman et al., 1990 from Ward, 1986[a]
		CO_2 carbon	0.7930	1.4	Kaufman et al., 1990 from Ward, 1986[a]
		CO carbon	0.1958	0.22	Kaufman et al., 1990 from Ward, 1986[a]
	Carbon released through termites	CH_4 carbon	0.0022	0.001	Martius et al., 1993, nd
		CO_2 carbon	0.9978	1.996	Assumed all C not released as methane is CO_2.
High trace gas scenario	Carbon released by combustion in initial burn	CH_4 carbon	0.0093	0.006	Kaufman et al., 1990 from Ward, 1986[a]
		CO_2 carbon	0.8779	1.55	Kaufman et al., 1990 from Ward, 1986[a]
		CO carbon	0.1335	0.15	Kaufman et al., 1990 from Crutzen, et al., 1985[a]
	Carbon released by combustion in reburns	CH_4 carbon	0.0171	0.011	Kaufman et al., 1990 from Greenberg et al., 1984[a]
		CO_2 carbon	0.7930	1.4	Kaufman et al., 1990 from Ward, 1986[a]
		CO carbon	0.2492	0.28	Kaufman et al., 1990 from Greenberg et al., 1984 and Ward, 1986[a]

Carbon released through termites	CH_4 carbon	0.0079	0.005	Goreau and de Mello, 1987
	CO_2 carbon	0.9978		Assumed all C not released as methane is CO_2

(a) Calculated from data presented by Kaufman et al. (1990: 382) as emission/kg fuel. Carbon content of the experimental fuel is assumed to be 48.2%, this value being chosen such that all combusted carbon is accounted for, either as CO_2, CH_4, CO, NMHC or particulate graphitic carbon.

TABLE XI: PARAMETERS FOR OTHER SOURCES OF GREENHOUSE GASES FROM LAND-USE CHANGE

Factor	Units	Value	Reference	Note
Soil carbon from top 20 cm	t C/ha	3.92	Fearnside, 1985	(a)
Cerrado biomass carbon	t C/ha	17.27	Fearnside, nd-a	(b)
Cattle CH_4	kg CH_4/head/year	55	Ahuja, 1990, based on Crutzen et al., 1986	
Cattle stocking rate	head/ha	0.3	Fearnside, 1979	(c)
Pasture soil N_2O	kg N_2O/ha/year	3.8	Luizão et al., 1989	(d)

(a) For conversion to pasture at Paragominas, based on Falesi (1976: 31 and 42) for carbon contents and Hecht (1981: 95) for soil densities.

(b) Based on conversion to pasture (total biomass 10.7 t/ha) of cerrado with average total biomass of 45 t/ha.

(c) Feeding capacity after 3 years.

(d) Full annual cycle under pasture and forest at Manaus.

TABLE XII: TRACE GAS PARAMETERS

Factor	Gases	Units	Value	Source
Intact forest soil sink	CH_4	t C/ha/yr	-0.0004	Keller et al., 1986
Burning release	N_2O[a][b]	t gas/t CO_2 emitted from burn	0.0002	Cofer et al., 1988 cited by Kaufman et al., 1990
Burning release	N_2O[c][d]	t gas/t C burned	0.0017	Calculated by Keller et al., 1991: 146 from Andreae et al., 1988
Burning release	NO_x[e]	t gas/t C burned	0.0079	Keller et al., 1991: 146
Intact forest release	NO_x[e]	t gas/ha/yr	0.0131	Kaplan et al., 1988; see Keller et al., 1991
Flaming burn release	Total particulates	t/t CH_4 gas from burn	3.33	Calculated by Kaufman et al., 1990: 380 from Ward and Hardy, 1984 and Ward, 1986
Smoldering burn release	Total particulates	t/t CH_4 gas from burn	1.67	Calculated by Kaufman et al., 1990: 380 from Ward and Hardy, 1984 and Ward, 1986
Flaming burn release	NMHC[b]	t/t CH_4 gas from burn	0.67	Derived using factor of 0.2 t NMHC/t particulates calculated by Kaufman et al., 1990: 380
Smoldering burn release	NMHC[b]	t/t CH_4 gas from burn	0.50	Derived using factor of 0.3 t CH_4/t particulates calculated by Kaufman et al., 1990: 380
Mixed burn release	NMHC[d][f]	t/t C burned	0.0131	Keller et al., 1991: 146 from measurements of Andreae et al., 1988
Intact forest release	NMHC	t gas/ha/yr	0.12	Rasmussen and Khalil, 1988: 1420

(a) Intact forest release accounted for in pasture soil calculation.

(b) Used in low trace gas scenario.

(c) results in 0.109 t gas/ha burned, or three times the 0.041 t gas/t C burned obtained using the parameter relating N_2O to CO_2.

(d) Used in high trace gas scenario.

(e) NO_x weight given in NO_2 basis (following Shine et al., 1990: 61).

(f) NMHC emission corresponds to 0.85 t gas/ha burned, much higher than values derived from methane, which are (for high and low trace gas scenarios, respectively): 0.36 and 0.43 t NMHC/ha burned for flaming combustion and 0.10 and 0.16 t NMHC/ha burned for smoldering combustion.

TABLE XIII: SOIL CARBON PARAMETERS AND CALCULATIONS

Parameters		Units	Value	Source
	Soil density in forest	g/cm^3	0.56	Hecht, 1981: 95
	Carbon in forest soil	% by wt	0.91	Falesi, 1976: 31 and 42
	Carbon in pasture soil	% by wt	0.56	Falesi, 1976: 31 and 42
	Top 20 cm C as fraction of 1 m C	% by wt	42	Fearnside, 1987
Calculated values				
Top 20 cm of soil:				
	Soil dry weight	t/ha	1,120	
	Carbon in forest soil	t/ha	10.19	
	Carbon in pasture soil compacted from top 20 cm of forest soil			
	Release from top 20 cm	t/ha	3.92	
	Release fraction of pre-conversion soil C	% by wt	38	
Top meter of soil:				
	Soil dry weight	t/ha	5,600	
	Carbon in forest soil	t/ha	24.27	
	Carbon in pasture soil	t/ha	14.93	
	Release from top meter	t/ha	9.33	
	Release fraction of pre-conversion soil C	% by wt	38	

TABLE XIV: NET COMMITTED GREENHOUSE GAS EMISSIONS BY SOURCE FOR 1990 CLEARING IN THE LEGAL AMAZON: LOW TRACE GAS SCENARIO

Source		Area affected (10^3 km^2)	Emissions (10^6 t of gas)					
			CO_2	CH_4	CO	N_2O	NO_x	NMHC
FOREST								
	Initial burn	13.8	228	0.74	17.66	0.05	0.56	0.49
	Reburns	13.8	55	0.27	8.58	0.01	0.15	0.14
	Termites above-ground decay	13.8	13	0.010				
	Other above-ground decay	13.8	422					
	Below-ground decay	13.8	249					
	Cattle[(a)]	6.1		0.010				
	Pasture soil[(a)]	6.1				0.002		
	Loss of intact forest sources and sinks[(a)]	7.3		0.0003			-0.01	-0.09
	Soil carbon (top 20 cm)	13.8	20					
	Regrowth	13.8	-65					
	Hydroelectric[(a)]	0.0		0.00				
	Forest subtotal		921	1.03	26.25	0.06	0.70	0.54
CERRADO								
	Initial burn	5.0	17	0.06	1.35	0.003	0.04	0.04
	Reburns	5.0	2	0.01	0.26	0.0003	0.005	0.004
	Termites above-ground decay	5.0	0.1	0.0001				
	Other above-ground decay	5.0	4					
	Below-ground decay	5.0	15					

Cattle[(a)]	5.0		0.008				
Pasture soil[(a)]	5.0				0.002		
Loss of intact <u>cerrado</u> sources and sinks[(a)(b)]	5.0		0.0002			-0.0004	-0.004
Soil carbon (top 20 cm)	5.0	7					
Regrowth	5.0	-9					
<u>Cerrado subtotal</u>		36	0.07	1.62	0.01	0.05	0.04
TOTAL FOR LEGAL AMAZON		958	1.10	27.86	0.06	0.74	0.58

(a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N_2O, hydroelectric methane) summed for 100-year period for consistency with IPCC 100-year horizon calculation.

(b) Intact <u>cerrado</u> source for NO_x and NMHC derived from the forest per-hectare emission assuming emission is proportional to the tree leaf dry weight biomass in each ecosystem. <u>Cerrado</u> tree leaf biomass (dry season) = 0.756 t/ha (dos Santos, 1989: 194). Forest (at Tucuruí, Pará) = 12.94 t/ha (Revilla Cardenas <u>et al</u>., 1982: 6).

TABLE XV: NET COMMITTED GREENHOUSE GAS EMISSIONS BY SOURCE FOR 1990 CLEARING IN THE LEGAL AMAZON: HIGH TRACE GAS SCENARIO

Source	Area affected (10^3 km^2)	Emissions (10^6 t of gas)					
		CO_2	CH_4	CO	N_2O	NO_x	NMHC
FOREST							
Initial burn	13.8	228	0.88	22.08	0.12	0.56	0.93
Reburns	13.8	55	0.43	10.93	0.03	0.15	0.25
Termites above-ground decay	13.8	13	0.01				
Other above-ground decay	13.8	422					
Below-ground decay	13.8	249					
Cattle[a]	6.1		0.01				
Pasture soil[a]	6.1				0.002		
Loss of intact forest sources[a]	7.3		0.0003			-0.01	-0.09
Soil C stock	13.8	20					
Regrowth	13.8	-65					
Hydroelectric[a]	0.0		0.00				
Forest subtotal		921	1.33	33.00	0.15	0.70	1.08
<u>CERRADO</u>							
Initial burn	5.0	17	0.07	1.69	0.009	0.043	0.07
Reburns	5.0	2	0.01	0.34	0.001	0.005	0.01
Termites above-ground decay	5.0	0.1	0.0001				
Other above-ground decay	5.0	4					
Below-ground decay	5.0	15					
Cattle[a]	5.0		0.01				

Pasture soil[a]	5.0				0.002		
Loss of intact *cerrado* sources[a][b]	5.0		0.0002			-0.0004	-0.004
Soil C stock	5.0	7					
Regrowth	5.0	-9					
Cerrado subtotal		36	0.09	2.03	0.012	0.05	0.07
TOTAL FOR LEGAL AMAZON		958	1.42	35.03	0.165	-0.74	1.16

(a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N20, hydroelectric methane) summed for 100-year period for consistency with IPCC 100-year horizon calculation.

(b) Intact *cerrado* source for NO_x and NMHC derived from the forest per-hectare emission assuming emission is proportional to the tree leaf dry weight biomass in each ecosystem. *Cerrado* tree leaf biomass (dry season) = 0.756 t/ha (dos Santos, 1989: 194). Forest (at Tucuruí, Pará) = 12.94 t/ha (Revilla Cardenas *et al*., 1982: 6).

TABLE XVI: NET COMMITTED EMISSIONS FROM 1990 DEFORESTATION WITH CO_2 EQUIVALENT, 100-YEAR TIME HORIZON

		Low trace gas scenario						High trace gas scenario						Contribution of each gas to total effect (%)	
Gas	Global warming potential[(a)]	Amount emitted (10^6 t of gas/year)			CO_2 equivalent (10^6 t of gas/year)			Amount emitted (10^6 t of gas/year)			CO_2 equivalent (10^6 t of gas/year)			Low trace gas scenario	High trace gas scenario
		Forest	Cerrado	Total	Forest	Cerrado	Total	Forest	Cerrado	Total	Forest	Cerrado	Total		
CO_2	1	921.23	36.41	957.41	921.23	36.41	957.41	921.23	36.41	957.64	921.23	36.41	957.64	95.26	91.63
CH_4	24.5	1.03	0.07	1.10	25.23	1.80	27.02	1.33	0.09	1.42	32.66	2.19	34.85	2.69	3.33
CO	0	26.25	1.62	27.86	0.00	0.00	0.00	33.00	2.03	35.03	0.00	0.00	0.00	0.00	0.00
N_2O	320	0.06	0.01	0.06	18.83	1.83	20.67	0.15	0.01	0.16	48.83	3.83	52.66	2.06	5.04
NO_x	0	0.70	0.05	0.74	0.00	0.00	0.00	0.70	0.05	0.74	0.00	0.00	0.00	0.00	0.00
NMHC	0	0.54	0.04	0.58	0.00	0.00	0.00	1.08	0.07	1.16	0.00	0.00	0.00	0.00	0.00
Total CO_2-equivalent gas (10^6 t)					965	40	1,005				1,003	42	1,045	100.0	100.0
CO_2-equivalent carbon (10^6 t)					263	11	274				273	12	285		

(a) IPCC 100-year values expressed as kg of CO_2 gas equivalent/kg of gas. The global warming potentials are from Albritton et al., 1995: 222.

Fig. 1


BRAZIL
RORAIMA
AMAPÁ
Rio Negro
BALBINA DAM
AMAZON RIVER
MANAUS
Rio Solimões (UPPER AMAZON)
ALTAMIRA
TUCURUÍ DAM
BELÉM
MARANHÃO
AMAZONAS
PARÁ
SAMUEL DAM
ACRE
RONDÔNIA
MATO GROSSO
TOCANTINS
GOIÁS
BRASÍLIA
LEGAL AMAZON
STATE BOUNDARY
RIVER
DAM
CITY
0 100 200 300 400 500 km

Fig. 2

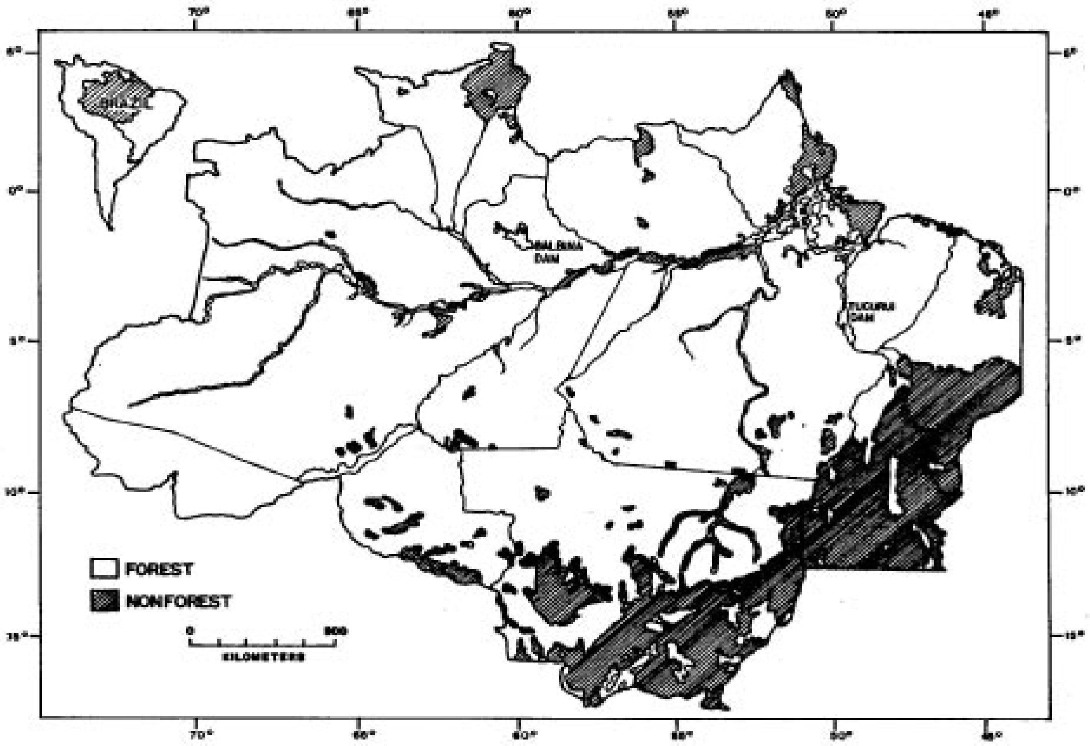

70°
60°
55°
50°
0°
5°
10°
BRAZIL
BALBINA DAM
TUCURUI DAM
FOREST
NONFOREST
0
KILOMETERS

Fig. 3

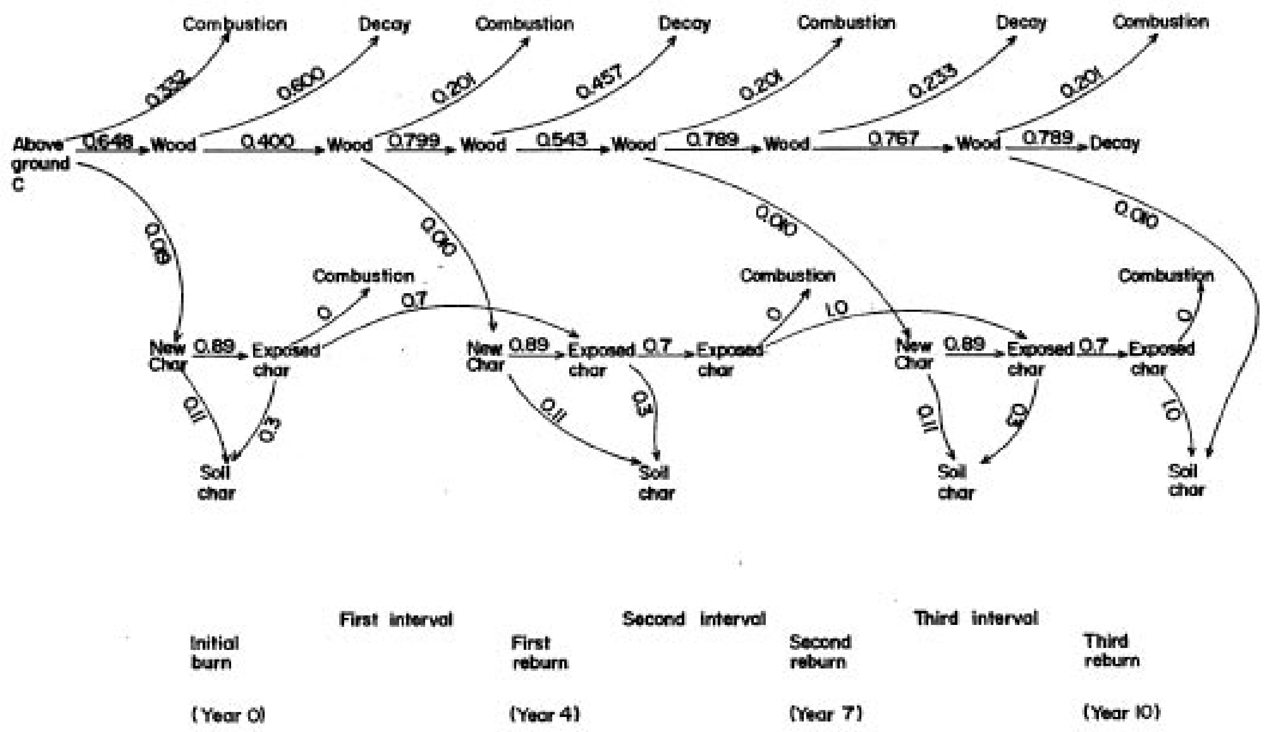
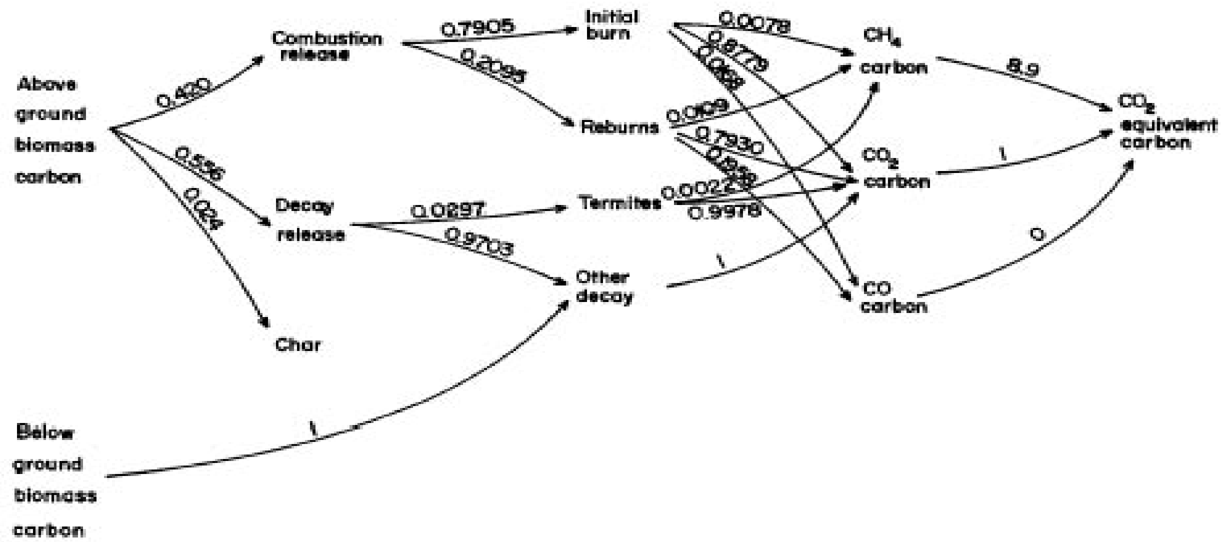

Combustion
Decay
Combustion
Decay
Combustion
Decay
Combustion
0.352
0.600
0.201
0.457
0.201
0.233
0.201
Above ground C
0.648
Wood
0.400
Wood
0.799
Wood
0.543
Wood
0.789
Wood
0.767
Wood
0.789
Decay
0.010
0.010
0.010
0.010
Combustion
Combustion
Combustion
0
0.7
0
1.0
0
New Char
0.89
Exposed char
New Char
0.89
Exposed char
0.7
Exposed char
New Char
0.89
Exposed char
0.7
Exposed char
0.11
0.3
0.11
0.3
0.11
0.3
1.0
Soil char
Soil char
Soil char
Soil char
First interval
Second interval
Third interval
Initial burn
First reburn
Second reburn
Third reburn
(Year 0)
(Year 4)
(Year 7)
(Year 10)

Fig. 4



Above ground biomass carbon
Below ground biomass carbon
Combustion release
Decay release
Char
Initial burn
Reburns
Termites
Other decay
CH4 carbon
CO2 carbon
CO carbon
CO2 equivalent carbon
0.420
0.556
0.024
0.7905
0.2095
0.0297
0.9703
0.0078
0.8779
0.0109
0.7930
0.0022
0.9978
8.9
1
1
1
0