CARBON EMISSIONS AND SEQUESTRATION IN FORESTS: CASE STUDIES FROM SEVEN DEVELOPING COUNTRIES

VOLUME 2: GREENHOUSE GAS EMISSIONS FROM DEFORESTATION IN THE BRAZILIAN AMAZON

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PREFACE

In January 1990, scientists and policymakers from around the world convened for a meeting of the Intergovernmental Panel on Climate Change (IPCC) in São Paulo, Brazil, to continue the ongoing discussions on emissions of greenhouse gases and global climate change. As part of the effort to further understand the sources of carbon dioxide (CO_2) and other major greenhouse gases, LBL and the University of Sao Paulo, with support from the U.S. Environmental Protection Agency, organized a workshop on tropical forestry and global climate change which was attended by the IPCC conference participants. Discussions at the workshop led to the establishment of the Tropical Forestry and Global Climate Change Research Network (F-7). The countries taking part in the F-7 Network -- Brazil, China, India, Indonesia, Malaysia, Mexico, Nigeria and Thailand -- possess among the largest tracts of the Earth's tropical forests and together experience the bulk of tropical deforestation.

The following research objectives were identified as the F-7 Network's priorities:

1. To improve and expand the body of knowledge about the extent of tropical deforestation through the use of available tools, including remote-sensing imagery, detailed biomass measurements and existing models.

2. To explore the dynamics of forest land use within the context of individual country's social and economic structures.

3. To identify alternative response options aimed at stemming deforestation and promoting sustainable land-use practices while maintaining each country's economic well-being. Meeting this objective includes carrying out an assessment of the economic costs of implementing various mitigative policies.

One of the strategies of this project was to rely on the work of indigenous researchers and institutions from each of the participating countries. This approach allowed for the integration of more precise, on-site information, some of which had not been previously published, into the more general and universally available base of knowledge. The Lawrence Berkeley Laboratory (LBL), which employed a similar approach to carry out a study on carbon emissions from energy use in developing countries (LDCs) (see Sathaye and Ketoff 1991), coordinated the work of the researchers and provided scientific and institutional support for the F-7 participants. The U.S. Environmental Protection Agency (EPA) financed the Network's work.

The information contained in this report represents the results of the first phase of the F-7 project, which had the explicit aim of providing quantitative data on forestry-related carbon emissions in the F-7 countries. This report contains the results of the first phase of the research effort. The next stage of the process will involve an assessment of response options in the forestry sector and the economics of undertaking these measures.

The following scientists and institutions participated in the research:

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The opinions expressed in this work are those of the authors and do not necessarily reflect those of the affiliated institutions or of the respective governments.

An international workshop to discuss the methods, results and policy issues associated with this project was held at the Lawrence Berkeley Laboratory in May 1991. We would like to thank the workshop participants and extend a special acknowledgement to Ken Andrasko of the U.S. EPA for his contribution. A full list of the workshop participants is provided in the appendix. The authors would also like to thank Nina Goldman for editing this work.

ABSTRACT

Deforestation in Brazilian Amazonia through 1990 had reached 415 X 10^3 km^2 (including old clearings), or 9.7% of the 4.3 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 22 X 10^3 km^2/year, falling to 19 X 10^3 km^2/year in 1989 and 13.8 X 10^3 km^2/year in 1990. The rate of forest loss in 1991 was 11.1 X 10^3 km^2/year, or 20% less than the 1990 rate on which the emissions calculations in this paper are based.

The annual rate of forest and *cerrado* loss in 1990 was releasing approximately 281-282 X 10^6 metric tons (MT) of carbon on 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 "committed carbon," or the carbon 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. To the extent that deforestation rates have remained constant, current releases from the areas deforested in previous years will be equal to the future releases from the areas being cleared now.

Considering the quantities of carbon dioxide, carbon monoxide, methane, nitrous oxide, NOx and non-methane hydrocarbons released raises the impact by 22-37%. The relative impact on the greenhouse effect of each gas is based on the Intergovernmental Panel on Climate Change (IPCC) calculations over a 20-year time period (including indirect effects). The six gases considered have a combined global warming impact equivalent to 343 to 386 million MT of CO_2-equivalent carbon, depending on assumptions regarding the release of methane and other gases from the various sources such as burning and termites. These emissions represent 7-8 times the 50 million MT annual carbon release from Brazil's use of fossil fuels, but bring little benefit to the country. Stopping deforestation in Brazil would prevent as much greenhouse emission as tripling the fuel efficiency of all the automobiles in the world. The relatively cheap measures needed to contain deforestation, together with the many complementary benefits of doing so, make this the first priority for funds intended to slow global warming.

1. INTRODUCTION

The present paper hopes to offer a structure for analyzing the greenhouse contribution of deforestation in Brazilian Amazonia. It is hoped that this structure will prove valuable beyond the short time that the series of numbers for greenhouse emissions presented here remains the current best estimate. As the rates and locations of deforestation activity change, and as better data become available on this and other important factors, the estimates can be continually updated. The decline in deforestation rates in recent years is largely explained by Brazil's deepening economic crisis and cannot be extrapolated into the future.

The greenhouse role of deforestation, especially deforestation in Brazil's Amazon region, is a subject of scientific controversy. Despite the wide range of opinions on the rate of deforestation and the amount of greenhouse gases this landscape transformation releases, even the most conservative estimates lead to the conclusion that deforestation makes significant contributions to atmospheric burdens of carbon dioxide (CO_2), methane (CH_4) and other heat-blocking gases. There is also a consensus that the meager and highly temporary benefits derived from deforestation are much more than counterbalanced by the losses, at least from the perspective of anyone except the few directly profiting from the clearing activity. Independent of the role of deforestation in the greenhouse effect, the other impacts of forest loss -- including non-greenhouse climatic changes and loss of biodiversity, indigenous cultures and opportunities for sustainable use of the forest -- provide ample justification for Brazil to take immediate steps to remove the motives now driving the clearing process. Greenhouse contributions add one more argument in support of this conclusion. Fortunately for the world, global warming would wreak some of its worst impacts on the temperate zone countries most capable of making the financial outlays needed to contain atmospheric buildup of greenhouse gases. The relatively cheap measures needed to slow tropical deforestation immediately present themselves as the first priority for funds intended to reduce global warming. Much more must also be done, of course, but stopping deforestation heads the list.

Brazil presently accounts for one-fifth of the global total of CO_2-equivalent carbon released by tropical deforestation. Brazil's vast expanses of still uncleared forest can be expected to increase this country's relative weight even further should the remaining remnants of forest in other parts of the tropics continue to succumb to deforestation. Only about 10% of Brazil's Amazon forest had been cleared by 1990 (Table 1; Fearnside *et al.*, nd-a). If the 13.8 X 10^3 km^2 of forest cleared in 1990 had been the last of the Amazon forest, then, in spite of being a great tragedy for biodiversity, greenhouse emissions would cease to be a major concern. However, with 90% of the forest still standing and at risk of rapid deforestation, the tremendous potential for future emissions is evident.

Table 1. Extent of deforestation in the Brazilian Legal Amazon

Political unit	Original forest area (km^2 x 10^3)	Deforested area (km^2 x 10^3) Jan 1978	Apr 1988	Aug 1989	Aug 1990	Deforested area (% of original forest area) Jan 1978	Apr 1988	Aug 1989	Aug 1990
Deforestation Exclusive of Hydroelectric Dams:									
Acre	154	2.5	8.9	9.8	10.3	1.6	5.8	6.4	6.7
Amapá	132	0.2	0.8	1.0	1.3	0.1	0.6	0.8	1.0
Amazonas	1561	1.7[a]	17.3[a]	19.3[a]	19.8[a]	0.1	1.1	1.2	1.3
Maranhao	155	63.9	90.8	92.3	93.4	41.2	58.5	59.5	60.2
Mato Grosso	585	20.0[a]	71.5[a]	79.6[a]	83.6[a]	3.4	12.2	13.6	14.3
Pará	1218	56.3	129.5	137.3	142.2	4.6	10.6	11.3	11.7
Rondônia	224	4.2	29.6	31.4	33.1	1.9	13.2	14.0	14.8
Roraima	188	0.1	2.7	3.6	3.8	0.1	1.5	1.9	2.0
Tocantins/Goiás	58	3.2	21.6	22.3	22.9	5.4	37.0	38.3	39.3
Legal Amazon	4275	152.1	372.8	396.6	410.4	3.6	8.7	9.3	9.6
Forest Flooded by Hydroelectric Dams:		0.1	3.9	4.8	4.8	0.0	0.1	0.1	0.1
Deforestation from All Sources:		152.2	376.7	401.4	415.2	3.6	8.8	9.4	9.7

Source: Fearnside *et al.*, nd-a.
Notes: (a) Maranhao values include 57.8 x 10^3 km^2, and Pará values include 39.8 x 10^3 km^2, of "old" (approximately pre-1960) deforestation now largely under secondary forest.

The vast size of Brazil's Amazon region is not matched by a proportionate amount of scientific knowledge of its forest. Political factors have led tropical research to be concentrated in the tiny vestiges of forest in such locations as Costa Rica, Puerto Rico and Panama. Costa Rica, for example, is 100 times smaller than Brazil's 5 X 10^6 km^2 Legal Amazon region (Fig. 1), yet has been the subject of many more research studies. Conclusions on global climate change require that special attention be devoted to Brazil. Likewise, discussions of tropical deforestation must not relegate Brazil to a list of caveats or exceptions to global generalizations. Deforestation in Brazil differs significantly from most other parts of the tropics because of the key role that Amazonian clearing plays in land speculation and in establishing land tenure, and because of the prominent place of cattle pasture in these social processes. In comparison with other tropical countries, these differences mean that Brazil has both less reason for allowing current rates of deforestation to continue and a greater chance of achieving significant reductions through government policy changes.

2. EXTENT AND RATE OF DEFORESTATION

The present paper uses estimates of the extent and rate of deforestation rate estimates by state derived from LANDSAT imagery (Tables 1 and 2). The average annual rates in the forested part of the Legal Amazon were 22 X 10^3 km^2 for the 1978-1988 period, 19 X 10^3 km^2 for 1988-1989 and 13.8 X 10^3 km^2 for 1989-1990 (Fearnside *et al.*, nd-a). The rate for 1990-1991 was 11.1 X 10^3 km^2. These rates cover only loss of primary forest within the portion of the region that was originally forested; rates of conversion of the *cerrado* are far less certain, but fortunately have less impact on greenhouse calculations due to the much lower biomass of savanna vegetation. *Cerrado* clearing rate for 1990 is assumed (guessed) to be 10 X 10^3 km^2/year, down from the value of 18 X 10^3 km^2/year estimated for 1988 (Fearnside, 1990a).

It should be noted that the deforestation rate estimates used here are much lower than those that have been used in several recent calculations of the global carbon budget. The World Resources Institute (WRI) Report for 1990-91 (WRI, 1990: 103) used 80 X 10^3 km^2/yr as the annual rate for the 1980s. Norman Myers (1989, 1990, 1991) placed the rate as of 1988 at 50 X 10^3 km^2/yr, and the Intergovernmental Panel on Climate Change (IPCC) later used this value as the basis for greenhouse emission calculations (IPCC, 1990: 101). Both estimates are based on calculations of the area burning derived from the number of fires estimated with the thermal infra-red band 3 (3.5-3.9 um) of the Advanced Very High Resolution Radiometer (AVHRR)--the sensor carried by the U.S. National Oceanographic and Atmospheric Administration (NOAA-9) meteorological satellite. The 80 X 10^3 km^2/yr rate used by WRI was that calculated for the year 1987, which had much more deforestation and burning than other years due to a combination of dry weather and a constitutional debate on confiscating forest areas from large ranchers for redistribution in a proposed agrarian reform program. The 1987 estimate (Setzer *et al.*, 1988, 1991), as well as the 48 X 10^3 km^2/yr value for 1988 estimated by Setzer and Pereira (1990) -- interviews concerning which provided the basis for the 50 X 10^3 km^2/yr estimate put forward by Myers and used by the IPCC -- suffer from severe (and possibly insoluble) methodological problems for estimating areas burned and for converting burning information into estimates of deforestation (reviewed in Fearnside, 1990a). The correction factors used to adjust for partially burning picture elements or pixels (0.7) and for the proportion

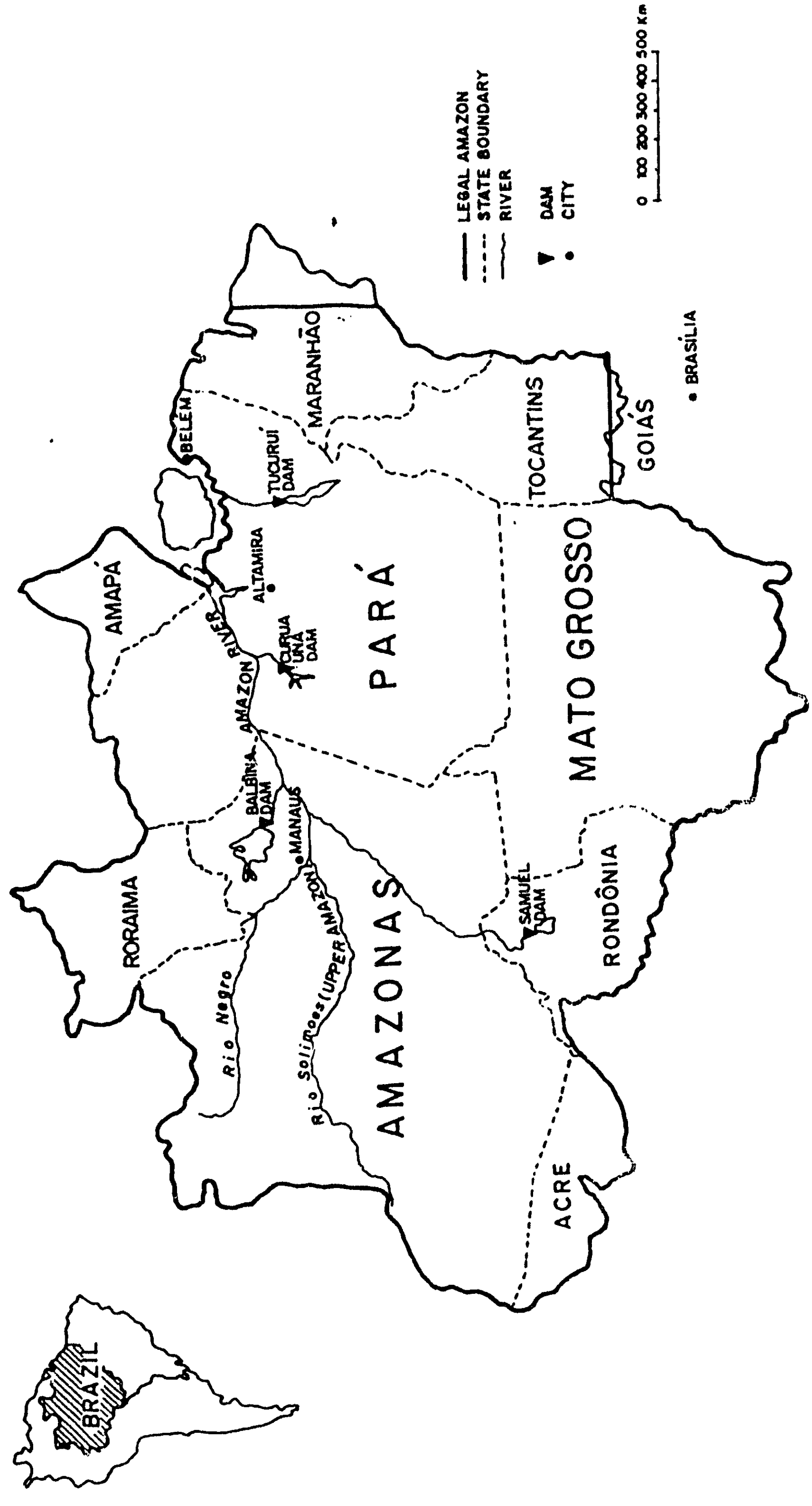

LEGAL AMAZON
STATE BOUNDARY
RIVER
DAM
CITY
0 100 200 300 400 500 Km
BRASÍLIA
GOIÁS
TOCANTINS
MARANHÃO
BELÉM
TUCURUÍ DAM
AMAPÁ
ALTAMIRA
CURUA UNA DAM
PARÁ
MATO GROSSO
AMAZON RIVER
BALBINA DAM
MANAUS
RORAIMA
AMAZONAS
Rio Negro
Rio Solimoes (UPPER AMAZON)
SAMUEL DAM
RONDÔNIA
ACRE
BRAZIL

Table 2. Rate of deforestation in the Brazilian Legal Amazon

Political unit	Deforestation rate ($km^2 \times 10^3/yr$)				Change in deforestation rate for 1988-1989 relative to 1978-1988		Change in deforestation rate for 1989-1990 relative to 1988-1989	
	1978-1988[a]	1978-1989[b]	1988-1989[c]	1989-1990	($km^2 \times 10^3/yr$)	(% change)	($km^2 \times 10^3/yr$)	(% change)
Deforestation Exclusive of Hydroelectric Dams:								
Acre	0.6	0.6	0.6	0.6	-0.1	-14	0.0	1
Amapá	0.1	0.1	0.2	0.3	0.1	190	0.1	48
Amazonas	1.6	1.5	1.3	0.5	-0.3	-17	-0.8	-59
Maranhao	2.7	2.4	1.4	1.1	-1.3	-47	-0.3	-22
Mato Grosso	5.1	5.1	6.0	4.0	0.8	16	-1.9	-33
Pará	7.3	7.0	5.8	4.9	-1.5	-21	-0.9	-15
Rondônia	2.3	2.3	1.4	1.7	-0.9	-37	0.2	16
Roraima	0.2	0.3	0.7	0.2	0.4	184	-0.5	-76
Tocantins/Goiás	1.7	1.7	0.7	0.6	-0.9	-56	-0.2	-21
Legal Amazon	21.6	21.1	18.1	13.8	-3.6	-17	-4.2	-23
Forest Flooded by Hydroelectric Dams:	0.4	0.4	1.0	0.0	0.6	156	-1.0	-100
Deforestation from All Sources:	22.0	21.5	19.0	13.8	-3.0	-14	-5.2	-27

Source: Fearnside *et al.*, nd-a

Notes: (a) Uses intervals of 10 years for all political units except Rondônia, Roraima and Tocanins/Goiás, for which the interval is 11 years. Intervals are rounded to the nearest year based on the state average image data for 1988 and the Legal Amazon average image date for 1978.

(b) Time interval of 11.6 years used for all political units.

(c) Time interval calculated by individual LANDSAT scene.

of the burning attributed to new forest clearing (0.4) could both be high by as much as a factor of two. A correction factor for partially burning pixels is difficult to derive because of large increases in the proportion of overestimation caused by small increases in fire temperature (a highly variable parameter) -- theoretical calculations show that a fire of only 900 m^2 is sufficient to trigger an entire AVHRR pixel of 1.2 X 10^6 m^2 (Robinson, 1991), although practical experience suggests that narrow flame fronts up to two km in length can escape detection (A.W. Setzer, personal communication, 1990). The correction factor for nonforest is high because *cerrado* was included in the numerator but not in the denominator when deriving the factor (Fearnside, 1990b). These methodological problems invalidate principal basis for the carbon calculations mentioned earlier. As of now there is no reliable way to measure directly the areas burning using an image from a single year (as was attempted in the thermal AVHRR studies): to estimate deforestation one still must have images from two years in the same place, and calculate by difference the increase in cleared area.

3. BIOMASS OF AMAZONIAN FORESTS

The initial biomass of the vegetation is an important factor affecting the magnitude of greenhouse emissions from deforestation. Estimates of this have been evolving over time. The controversy over biomass is summarized in Table 3. The biomass estimate used in the present paper (372 MT/ha total biomass for forests cleared in 1990) is based on much more data than the earlier estimates. It also indicates a substantial increase in the biomass per hectare estimated for the locations currently the focus of deforestation activity in Amazonia. It is higher by a factor of two than the 155.1 MT/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 169.6 MT/ha above-ground estimate by Brown *et al.* (1989) used as total biomass by Houghton (1991) for carbon emission estimates. The estimate is also higher than the 211 MT/ha total biomass estimated for areas cleared in 1988 for emissions calculations (Fearnside, 1991); a major reason for the increase is better data for biomass in the southern portion of the region where deforestation activity is concentrated.

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 2), and is apportioned between 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.

Table 3. Amazon forest biomass controversy

Total Biomass Reported (MT/ha)	Total biomass equivalent (including components omitted in published value) (MT/ha)	Source
155.1	171	Brown and Lugo, 1984
362	362	Fearnside, 1985a
254	254	Fearnside, 1986b, 1987a
169.6	251	Brown *et al.*, 1989
247[a]/211[b]	247[a]/211[b]	Fearnside, 1991 nd-a
227[c]/289[d]		Brown and Lugo, 1992
272[a]/320[e]	272[a]/320[e]	Fearnside, 1992
372[f]/394[a]	372[f]/394[a]	This estimate

Notes: (a) All forests in Brazilian Legal Amazon.
(b) Forests being cleared in 1988 in Brazilian Legal Amazon.
(c) From RADAMBRASIL data.
(d) From FAO data.
(e) Dense forests only.
(f) Forests being cleared in 1990 in the Brazilian Legal Amazon.

The different types of vegetation present in the Legal Amazon are summarized in Table 4 and the area of each is given by state in Table 5. These areas have been measured (Fearnside and Ferraz, nd) from a digitized version of the 1:5,000,000 scale vegetation map of Brazil published by the Brazilian Institute for Forestry Development (IBDF -- since incorporated into the Brazilian Institute for the Environment and Renewable Natural Resources - IBAMA) and the Brazilian Institute for Geography and Statistics (IBGE) (Brazil, IBDF and IBGE, 1988). The IBDF/IBGE (IBAMA) map code used indicates 29 vegetation types within the Brazilian Legal Amazon, of which 19 are considered here to be forest. This is a liberal definition of forest, including all ecotones between a forest and a non-forest 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. The areas that were originally forest and non-forest using this definition are mapped in Figure 2.(1)

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 "ecosystems," there are a total of 112 different ecosystems 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 emissions. Table 6 presents the areas of each vegetation type inside of protected areas, which have been subtracted from the areas of the vegetation types present for the purpose of apportioning the deforestation activity. The resulting estimate of the approximate 1990 clearing rate in each ecosystem type is presented in Table 7.

Biomass loading (biomass per hectare) of the different forest types is estimated from forest volume inventories in two major surveys, one carried out by the RADAMBRASIL project in the 1970s and one by the Food and Agriculture Organization of the United Nations (FAO) in the 1950s. A total of 2892 ha of usable data have been extracted from these studies for vegetation types classified as forest. Almost 90% of this is surveys by RADAMBRASIL with measurements of trees to a minimum diameter at breast height (DBH) of 31.8 cm; the remainder is from FAO surveys with measurements to a minimum diameter of 25 cm DBH. Almost all of the data are from one-hectare sample plots. The original data are scattered through the over 50 volumes and annexes that comprise these studies. The RADAMBRASIL study is a veritable labyrinth, with its vegetation key changing from one volume to the next. The RADAMBRASIL vegetation maps were drawn at a scale of 1:250,000 and published at a scale of 1:1,000,000; the vegetation classification for these maps is more detailed than that for the 1:5,000,000 IBDF/IBGE (IBAMA) map used here (Table 4). The RADAMBRASIL and FAO vegetation classifications were translated to the IBAMA code, and data with unresolved inconsistencies were discarded (Fearnside and Bliss, nd).

Table 4. Vegetation types in the Brazilian Legal Amazon

Category	Code	Group	Subgroup	Class
DENSE FOREST	Da-0	Ombrophyllous forest	dense forest	alluvial Amazonian
	Db-0	Ombrophyllous forest	dense forest	lowland Amazonian
	Dm-0	Ombrophyllous forest	dense forest	montane Amazonian
	Ds-0	Ombrophyllous forest	dense forest	submontane Amazonian
NON-DENSE FOREST	Aa-0	Ombrophyllous forest	open	alluvial
	Ab-0	Ombrophyllous forest	open	lowland
	As-0	Ombrophyllous 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 arboreal
	Ld-0	Woody oligotrophic vegetation of swampy and sandy areas		dense arboreal
	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 -- ombrophyllous forest
	ON-0	Areas of ecological tension and contact		Ombrophyllous forest--seasonal forest
	Pf-0	Areas of pioneer formations		fluvio-marine influence
	SM-0	Areas of ecological tension and contact		savanna--dense ombrophyllous forest
	SN-0	Areas of ecological tension and contact		savanna--seasonal forest
	SO-0	Areas of ecological tension and contact		savanna--ombrophyllous forest
NON-FOREST	Ep-0	Steppe	caatinga	parkland
	Pa-0	Areas of pioneer formations		fluvial influence
	rm-0	Ecological refugium	high altitude	montane
	Sa-0	savanna	cerrado	open arboreal
	Sd-0	savanna	cerrado	dense arboreal
	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 arboreal
	Tp-3	Steppe-like savanna	Roraima grasslands	parkland

Table 5. Area of natural vegetation present in the Brazilian Legal Amazon (km²)

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grasso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total present
DENSE FOREST	Da-0		9,011	164,867	105	1,116	76,570	2,704	3,326	2,610	260,309
	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	968,354	24,679	24,270	657,424	19,377	117,927	5,665	1,945,150
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								970		970
	Ld-0								10,967		10,967
	Lg-0								9,767		9,767
	LO-0			172,607					30,184		202,791
	ON-0		30			168,069	2,991	4,801	3,045		178,936
	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	6,079	515,394	12,709	486,198	386,893	160,363	69,594	23,675	1,785,876
	Subtotal all forests	141,897	116,607	1,483,748	37,388	510,468	1,044,317	179,740	187,521	29,340	3,731,026

(continued on following page)

Table 5 (continued). Area of natural vegetation present in the Brazilian Legal Amazon (km^2)

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grasso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total present
NON-FOREST	Ep-0							904			904
	Pa-0		15,157	12,778	2,517	14,738	27,162	8,690			81,042
	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				22	10,490	5,057		15,481	7,113	38,163
	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	101,048	274,286	51,572	23,286	37,061	160,754	693,067
	Total	141,897	141,802	1,503,613	138,436	784,754	1,095,889	203,026	224,582	190,094	4,424,093

Notes: Areas in km^2 measured from 1:5,000,000 vegetation map (Brazil, IBAMA/IBOE, 1989). These areas do not reflect losses due to recent deforestation.

Table 6. Area of protected vegetation in the Brazilian Legal Amazon

Vegetation type[a]	Code	Area protected (km²)									
		Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total protected
DENSE FOREST	Da-0		305	5,316			7	297		58	5,983
	Db-0			21,994	2,872		5,914				30,780
	Dm-0			3,902					565		4,467
	Ds-0		59	3,614			7,999	558	5,384		17,614
	subtotal	0	364	34,826	2,872	0	13,920	855	5,949	58	58,844
NON-DENSE FOREST	Aa-0			99							99
	Ab-0	992		2,779				88			3,859
	As-0			648			75	4,915			5,638
	Cs-0										0
	Fa-0										0
	Fs-0									430	430
	La-0			601							601
	Ld-0			485					476		961
	Lg-0										0
	LO-0			15,029					1,581		16,610
	ON-0										0
	Pf-0		1,547								1,547
	SM-0										0
	SN-0					2,592					2,592
	SO-0		796					2,993			3,789
	Subtotal	992	2,343	19,641	0	2,592	75	7,996	2,057	430	36,126
	Subtotal all forests	992	2,707	54,467	2,872	2,592	13,995	8,851	8,006	488	94,970

(continued on following page)

Table 6 (continued). Area of protected vegetation in the Brazilian Legal Amazon.

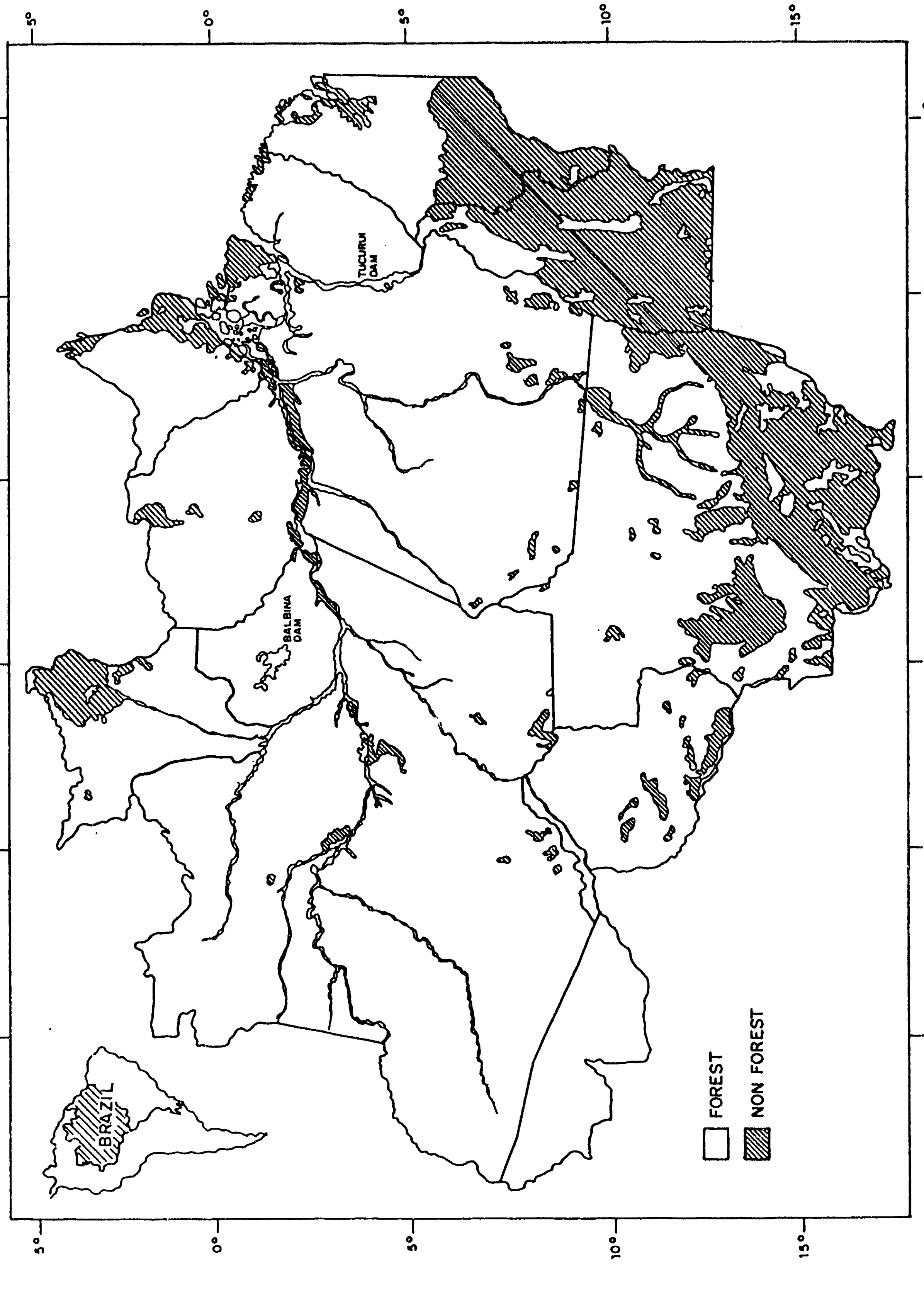
Vegetation type[a]	Code	Area protected (km²)									
		Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total protected
NON-FOREST	Ep-0										0
	Pa-0		5,739	54				1,569			7,362
	rm-0										0
	Sa-0					1,336		3,513			4,849
	Sd-0										0
	Sg-0					854					854
	Sp-0		158							4,064	4,222
	ST-0										0
	Td-3										0
	Tp-3										0
	Subtotal	0	5,897	54	0	2,190	0	5,082	0	4,064	17,287
	Total	992	8,604	54,521	2,872	4,782	13,995	13,933	8,006	4,552	112,257

Notes: Vegetation presently unaltered according to 1:5,000,000 vegetation map (Brazil, IBDF/IBGE, 1988).

Table 7. Approximate 1990 clearing rate in each ecosystem type in the Brazilian Legal Amazon (10^3 ha/year)

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/ Goiás	Total
DENSE FOREST	Da-0		2.00	5.95	0.34	0.88	36.43	2.36	0.30	5.20	53.46
	Db-0	6.50	0.50	22.10	63.51		75.26	2.03	0.92		170.82
	Dm-0		0.03	0.23			1.63		1.80		3.69
	Ds-0	0.21	22.81	6.50	6.40	18.35	192.85	13.78	7.02	6.23	274.16
	subtotal	6.70	25.34	34.79	70.26	19.24	306.16	18.17	10.04	11.43	502.12
NON-DENSE FOREST	Aa-0	4.19		2.45			0.38	2.23			9.25
	Ab-0	44.90		7.76				40.19			92.85
	As-0			1.38		98.79	136.16	71.48	0.76	2.48	311.04
	Cs-0				11.81	0.58	2.56			0.23	15.19
	Fa-0					2.82					2.82
	Fs-0					19.28		7.57	0.09	1.83	28.77
	La-0								0.09		0.09
	Ld-0								0.94		0.94
	Lg-0								0.88		0.88
	LO-0			5.87					2.57		8.44
	ON-0		0.01			133.23	1.42	4.71	0.27		139.64
	Pf-0		0.06		6.73		1.85				8.65
	SM-0				1.24						1.24
	SN-0			0.04	21.17	111.13	13.23	4.69	0.08	29.48	179.82
	SO-0		0.79	1.02		17.54	28.42	18.57	0.38	13.35	80.08
	Subtotal	49.10	0.86	18.51	40.94	383.36	184.04	149.43	6.06	47.37	879.68
	Subtotal All Forests	55.80	26.20	53.30	111.20	402.60	490.20	167.60	16.10	58.80	1381.80

Notes: Areas in km^2 measured from 1:5,000,000 vegetation map (Brazil, IBAMA/IBOE, 1989). These areas do not reflect losses due to recent deforestation.



TUCURUI DAM
BALBINA DAM
BRAZIL
FOREST
NON FOREST
45°
50°
55°
60°
65°
70°
5°
0°
5°
10°
15°

All biomass values given here and elsewhere in this paper refer to oven dry weight biomass. Unless otherwise noted, the 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%).

The parameters used for deriving the biomass estimates are given in Table 8. It should be noted that these parameters lead to estimated biomass values substantially higher than those derived by Brown and Lugo (1992) from the FAO dataset and from a summary of a portion of the RADAMBRASIL dataset covering the northern part of the region. The difference is largely because of biomass components omitted from the Brown and Lugo estimates, including palms, vines, trees smaller than the 10 cm DBH, dead biomass and below-ground biomass (see Fearnside, 1992). All of these components must be added to the estimates for use in estimating carbon stocks for greenhouse calculations.

Direct measurements of above-ground forest biomass partitioning are necessary to derive factors for estimating components such as vines, understory, litter and dead wood. Available data are presented in Table 9. Below-ground biomass is derived from the available studies presented in Table 10.

The total biomass is derived for each of the approximately 2900 samples, and the average for each ecosystem type is calculated. Sample sizes in hectares are given in Table 11. Of the 78 forested ecosystem types, 45 (58%) have forest volume data available in the RADAMBRASIL or FAO datasets, and 33 (62%) do not. Fortunately, most of the ecosystem types without data are relatively minor in importance from the standpoint of current greenhouse emissions. Of estimated biomass cleared in 1990, they total only 21%. Of this, 60% is represented by only three ecosystem types: As-0 in Mato Grosso, As-0 in Rondônia and SN-0 in Tocantins.[2] For the ecosystems with no forest volume measurements, the mean biomass for the areas sampled in the same vegetation type (in the other states) is used as a substitute. For five of the 19 forest types, no measurement exists for any state. Seven of the 33 ecosystems without data fall into this category. All of these are in the "non-dense" forest category, and, fortunately, none represents a major ecosystem from an emissions standpoint. The mean for sampled areas in non-dense forests was used as a substitute for these seven values. Vegetation types with no sample in any state represent only 0.9% of the estimated biomass cleared in 1990; of this small amount, 73.4% is in one vegetation type (Pf-0). The mean biomass per hectare in each of the 78 forest types, including the values substituted as described above, are presented in Table 12. It is evident that significant variation exists between states and between forest types.

Table 8. Parameters for deriving biomass estimates from RADAMBRASIL and FAO forest volume data

Derivation	Factor	Multiplier	Source	basis
Calculation of stemwood volume for trees of DBH > 10 cm:	Volume expansion factor (30-10 cm DBH) (RADAMBRASIL)	1.25	Brown and Lugo 1992	c
	Volume expansion factor (25-10 cm DBH) (FAO)	1.22	Brown and Lugo 1992	
Conversion of stemwood volume to biomass:	Wood density (basic specific gravity)	0.69	Brown *et al.* 1989; Brown and Lugo 1992	d
	Biomass expansion factor	a	Brown and Lugo 1992	e
Adjustments to above-ground live biomass[b]:	Hollow trees	0.9077	Fearnside 1992	f
	Vines	1.0425	Fearnside 1992	g
	Other non-tree components	1.0021	Fearnside 1992	h
	Palms	1.0350	Fearnside 1992	i
	Trees < 10 cm DBH	1.1200	Fearnside 1992	j
	Trees 30-31.8 cm DBH	1.0360	Fearnside 1992	k
	Bark (volume & density)	0.9856	Fearnside 1992	l
	Sapwood (volume & density)	0.9938	Fearnside 1992	m
	Form factor	1.1560	Fearnside 1992	n
Adjustments for other components[b]:	Dead above-ground biomass:	1.0903	Fearnside 1992	o
	Below-ground:	1.196	Table 10	p

(continued on following page)

Notes: (a) Biomass expansion factor (BEF) from Brown and Lugo, 1992: BEF=Exp (3.213-(0.506 ln (SB))) for SB<190 MT/ha; 1.74 for SB>190 MT/ha, where SB=stand biomass in MT/ha for trees > 10 cm DBH. SB=wood density x wood volume. Wood volume = volume reported by RADAMBRASIL or FAO, multiplied by the appropriate volume expansion factor.

(b) The adjustments to above-ground live biomass are with respect to the biomass values as defined by Brown and Lugo, 1992 (live stemwood >10 cm DBH), while the adjustments for other components are with respect to above-ground live biomass after the above corrections.

(c) For dense forest: 80% of volume of trees > 10 cm DBH is in trees >30 cm DBH. Non-dense forest = 1.50 (67% of volume > 30 cm DBH).

(d) 21 1-ha plots in Pará by Heinsdijk, 1958a,b; one 0.08-ha plot near Manaus by Prance *et al.*, 1976.

(e) All cases (pan tropical) reviewed in Brown *et al.*, 1989.

(f) Calculated from N. Higuchi, personal communication, 1991.

(g) Fearnside *et al.*, nd-c, nd-d; Revilla Cardenas, 1986:39, 1987:51, 1988:76-77.

(h) Klinge *et al.*, 1975:116

(i) Klinge *et al.*, 1975:116; Fearnside *et al.*, nd-a.

(j) Jordan and Uhl, 1978:392

(k) Brazil, Projeto RADAMBRASIL, 1973, 5:IV/12

(l) density: D.A. da Silva, personal communication, 1991; weight: Revilla Cardenas, 1986:38, 1987:51, 1988:76-77.

(m) 13 species at Jari (Reid Collins & Associates Ltd., 1977); 15 species at Manaus (INPA, CPPF, unpublished data)

(n) Form factors by size class in 309 trees at Manaus: N. Higuchi *et al.*, unpublished data; size classes: Coic *et al.*, 1991.

(o) Klinge *et al.*, 1975; Revilla Cardenas, 1986:39, 1987:51, 1988:76-77; Martinelli *et al.*, 1988:35

(p) Klinge *et al.*, 1975 (Manaus); Russell, 1983 (Jari); D. Nepstad, unpublished data (Paragominas)

Table 9. Direct measurements of forest biomass and components

Location (State)	Forest type	Dry weight of component (MT/ha)								Percent of above-ground live dry weight (%)					Tot. A-g+ dry wt.	Vine % of tot. a-g	Direct survey area	Source (page)
		A-g live biomass	Bark	Vines	Roots	Under-story*	Dead wood	Litter	Total dead ***	Bark	Vines	Root mat	Under-story	Total dead	(MT/ha)	(%)	(m²)	
DENSE FORESTS:																		
Kararao Dam++ (Pará)	Dense riparian	186.1	11.76	2.81	3.34	5.55	11.17	8.29	19.46	6.32	1.51	1.79	2.98	10.46	205.56	1.37	625	a(51)
Samuel Dam (Rondônia)	Dense upland	387.86	44.24	4.59	1.96	12.96	1.68	13.56	15.24	11.41	1.18	0.51	3.34	3.93	403.1	1.14	625	b(39)
Babaquara Dam (Pará)	Dense riparian	297.38	19.55	9.74	4.01	9.58	12.32	10.5	22.82	6.57	3.28	1.35	3.22	7.67	320.2	3.04	2500	c(76)
Babaquara Dam (Pará)	Dense upland	198.27	9.08	9.02	1.34	9.15	8.87	12.31	21.18	4.58	4.55	0.68	4.61	10.68	219.45	4.11	1875	c(77)
Reserva Egler (Amazonas)		357									6.2			9.24	390		2000	d
Fazenda Dimona (Amazonas)											2.82						600	e
Altamira (Pará)				32.61							10.19				272.46	11.97	900	f
Samuel Dam (Rondônia)		303					27	10	37.00					12.21	340			g(35)
MEAN										7.22	4.25	1.08	3.54	9.03	1148.31	9.66		
NON-DENSE FORESTS:																		
Kararao Dam++ (Pará)	Open upland	126.05	6.45	2.87	3.55	5.99	7.46	9.53	16.99	5.12	2.28	2.82	4.75	13.48	143.04	2.01	625	b(54)
Samuel Dam (Rondônia)	mata de baixio**	362.45	16.48	10.77	10.6	2.59	5.52	5.35	10.87	4.55	2.97	2.92	0.71	3.00	373.32	2.88		a(39)

Sources:
(a) Revilla Cardenas, 1987
(b) Revilla Cardenas, 1986
(c) Revilla Cardenas, 1988
(d) Klinge *et al.*, 1975
(e) Fearnside *et al.*, nd-c
(f) Fearnside *et al.*, nd-d
(g) Martinelli *et al.*, 1988

Notes:
* woods and leaves
** Open upland forest on poorly drained terrain
*** wood litter
\+ A-g = Above-ground
\++ renamed Belo Monte Dam

Table 10. Below-ground biomass in Amazonian forests

Location	Above-ground live (MT/ha)	Above-ground total (MT/ha)	Below-groun d biomass (MT/ha)	Total biomass (MT/ha)	Root/shoot ratio	Percent below-ground (live+dead)	Source
Manaus, Amazonas	357.0	390.0	122.5	512.5	0.31	23.90	(a)
Jari, Pará	368.91	393.24	56.96	450.2	0.14	12.65	(b)
Paragominas, Pará	365.0	428.0	32.0	440.0	0.07	7.27	(c)
Mean	363.64	403.75	70.49	467.57	0.17	15.08	

Sources:

(a) Klinge *et al.*, 1975; Klinge and Rodrigues, 1973.

(b) Russell, 1983:29; root mat (12.49 MT/ha) considered as below-ground. Litter (5.66 MT/ha) and "vines & surface roots" (3.46 MT/ha) considered as above-ground.

(c) Uhl *et al.*, 1988 for above-ground components except above-ground roots (30 MT/ha) (D. Nepstad, pers. comm., 1991 cited by Brown *et al.*, nd); Below-ground from Nepstad, 1989 cited by Brown *et al.*, nd.

The biomass stock in each ecosystem type can be calculated by multiplying the per-hectare biomass (Table 12) by the area in hectares (values from Table 5 multiplied by 100 ha/km^2). Table 13 gives the approximate biomass stock cleared in 10^6 metric tons (MT) for each ecosystem in the Legal Amazon. For the region's forests as a whole, the mean biomass loading (MT/ha) for biomass present (weighted by the area of each ecosystem present) is estimated at 394 MT/ha. In Table 12 the loading for biomass cleared in 1990 (weighted by the deforestation rate in each state) is calculated at 372 MT/ha. The forest areas cleared in 1990 are concentrated in lower biomass vegetation types along the southern fringe of the region (Table 13). The biomass in the region as a whole is about 6% higher than the average in the areas cleared in 1990, a difference equivalent to over 800 km^2 of forest clearing.

The above biomass calculations apply only to forest. Clearing in the non-forest areas is assumed to be in *cerrado* or equivalent biomass vegetation. *Cerrado* biomass is not derived from the 120 ha of RADAMBRASIL forest volume information available (Table 11), but rather from firewood volume surveys (Table 14). The mean of the three available estimates corresponds to a total biomass of 45 MT/ha.

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 emissions (e.g., Fearnside, 1985a, 1987a, nd-a), 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. 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, nd-b).

The fate of land that is cleared can be approximated using information on the behavior of farmers and ranchers in Amazonia today. The consequences of continuation of the same patterns can be calculated using a Markov matrix of transfer probabilities between states. The annual probabilities of transfer between farmland, productive pasture, degraded pasture and secondary forest are summarized in Figure 3 for land that is deforested (based on Fearnside, 1989a).

Table 11. Surveyed area of ecosystem types in the Brazilian Legal Amazon <ha with complete data>

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/Goiás	Total
DENSE FOREST	Da-0		1	249	0	4	17	5	6	0	282
	Db-0	11	6	363	18		1,028	0	10		1,436
	Dm-0		0	2			0		25		27
	Ds-0	12	30	174	0	51	164	0	47	4	482
	subtotal		37	788	18	55	1,209	5	88	4	2,204
NON-DENSE FOREST	Aa-0	12		26			0	0			38
	Ab-0	27		53				12			92
	As-0			8		0	86	0	0	0	94
	Cs-0				0	1	0			0	1
	Fa-0					7					7
	Fs-0					22		9	0	0	31
	La-0								0		0
	Ld-0								0		0
	Lg-0								0		0
	LO-0			219					2		221
	ON-0		0			101	0	11	20		132
	Pf-0		0		0		0				0
	SM-0				0						0
	SN-0			2	0	66	2	0	2	0	72
	SO-0		0	2		13	24	0	0	0	39
	Subtotal		0	310	0	210	112	32	24	0	688
	Subtotal all forests		37	1,098	18	265	1,321	37	112	4	2,892

(continued on following page)

Table 11 (continued). Surveyed area of ecosystem types in the Brazilian Legal Amazon <ha with complete data>

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/Goiás	Total
NON-FOREST	Ep-0							0			0
	Pa-0		0	1	0	0	0	0			1
	rm-0								0		0
	Sa-0			0	0	109	0	0		0	109
	Sd-0				0	9	0			0	9
	Sg-0				0	0	0		0	0	0
	Sp-0		1	0	0	0	0	0	0	0	1
	ST-0					0					0
	Td-3								0		0
	Tp-3								0		0
	Subtotal		1	1	0	118	0	0	0	0	120
	Total		38	1,099	18	383	1,321	37	112	4	3,012

Notes: (a) Areas in km^2 measured from 1:5,000,000 vegetation map (Brazil, IBAMA, 1989). These areas do not reflect losses due to recent deforestation.

Table 12. Biomass per hectare: Means by ecosystem type, vegetation type and state (MT/ha)

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/Goiás	Area-weighted mean
DENSE FOREST	Da-0		411	446	434	267	360	275	366	434	374
	Db-0	388	507	400	400		485	461	364		438
	Dm-0		381	298			381		387		379
	Ds-0	328	512	399	360	352	432	360	365	90	418
	Dense forests	386	504	407	396	348	436	360	369	247	420
NON-DENSE FOREST	Aa-0	390		399			492	395			398
	Ab-0	401		404				351			380
	As-0			444		330	319	330	330	330	326
	Cs-0				337	337	337			337	337
	Fa-0					325					325
	Fs-0					354		414	371	371	371
	La-0								380		380
	Ld-0								380		380
	Lg-0								380		380
	LO-0			433					379		417
	ON-0		352			339	352	482	346		344
	Pf-0		380		380		380				380
	SM-0				380						380
	SN-0			366	344	343	428	344	277	344	350
	SO-0		341	499		306	346	341	341	341	337
	non-dense forests	400	344	421	349	337	333	348	368	344	344
	all forests	398	499	412	379	338	397	349	368	325	372

Table 13. Approximate biomass cleared in 1990 in each ecosystem type in the Brazilian Legal Amazon (10^6 MT/year)

Category	Code	Acre	Amapá	Amazonas	Maranhao	Mato Grosso	Pará	Rondônia	Roraima	Tocantins/Goiás	Total
DENSE FOREST	Da-0		823	2,654	4	236	13,100	649	109	2,256	19,974
	Db-0	2,519	255	8,838	25,376		36,503	934	334		74,758
	Dm-0		10	70			619		698		1,397
	Ds-0	67	11,682	2,592	2,307	6,458	83,340	4,962	2,563	561	114,532
	subtotal	2,586	12,769	14,153	27,829	6,694	133,562	6,545	3,705	2,817	210,661
NON-DENSE FOREST	Aa-0	1,635		976			188	881			3,681
	Ab-0	18,008		3,134				14,110			35,252
	As-0			610		32,603	43,500	23,589	250	818	101,369
	Cs-0				3,986	197	865			79	5,126
	Fa-0					916					916
	Fs-0					6,822		3,136	35	680	10,672
	La-0								33		33
	Ld-0								357		357
	Lg-0								333		333
	LO-0			2,543					972		3,515
	ON-0		2			45,206	501	2,268	94		48,072
	Pf-0		24		2,556		704				3,284
	SM-0				470						470
	SN-0			15	7,292	38,153	5,669	1,615	22	10,155	62,922
	SO-0		269	508		5,374	9,839	6,329	131	4,549	27,000
	Subtotal	19,643	295	7,787	14,303	129,270	61,266	51,929	2,227	16,281	303,002
	Subtotal all forests	22,230	13,065	21,940	42,132	135,964	194,828	58,474	5,932	19,099	513,663
AVERAGE BIOMASS/HA CLEARED	Dense forests	386	504	407	396	348	436	360	369	247	420
	non-dense forests	400	344	421	349	337	333	348	368	344	344
	All forests	398	499	412	379	338	397	349	368	325	372

Table 14. Cerrado biomass

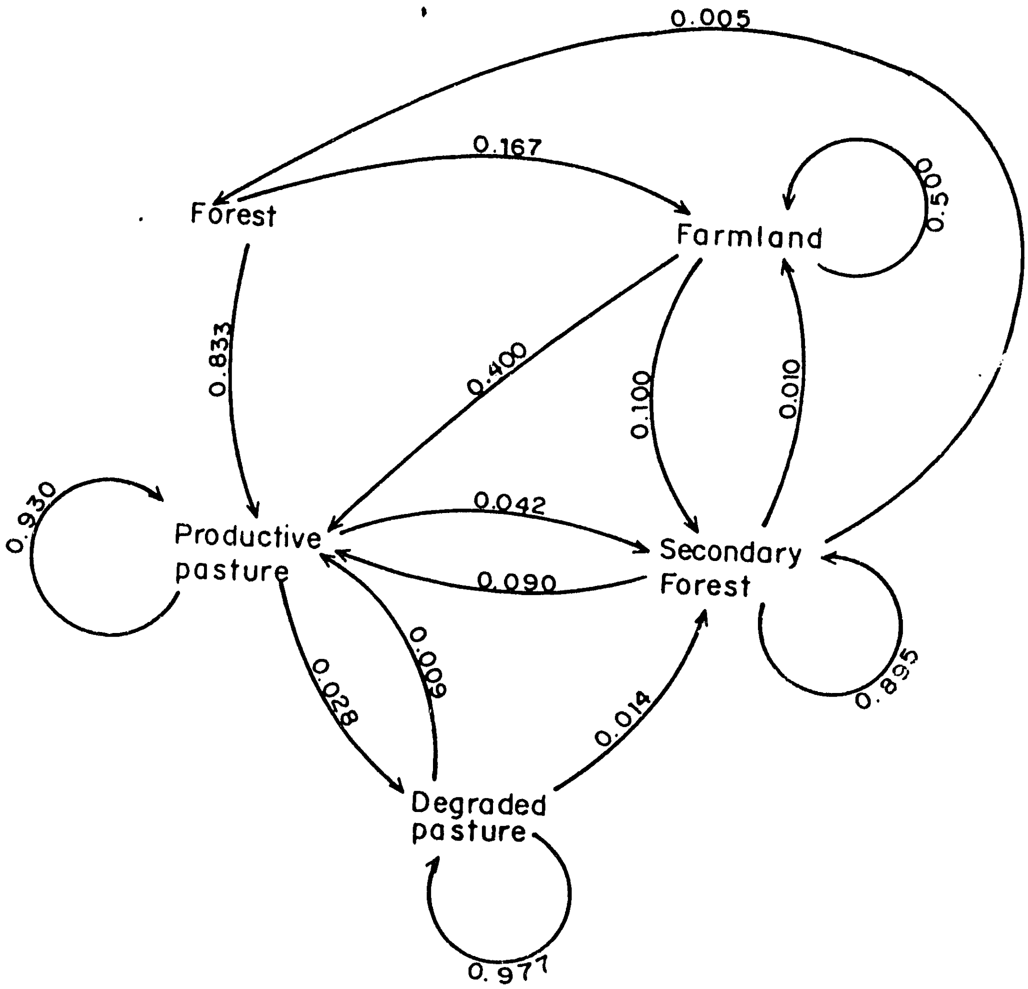
Location	Firewood volume (steres/ha) (a)	Firewood dry weight (MT/ha) (b)	Above-ground biomass (MT/ha) (c)	Total biomass (MT/ha) (d)	Firewood vol. source (page #)
Grande Carajas	120	47	52	82	e(70)
Central Mato Grosso	25	10	11	17	f(445)
Southern Mato Grosso	54	21	24	37	g(363)
Mean	66	26	29	45	

Notes: (a) steres are m^3 of stacked firewood, including air spaces between pieces.
(b) 390 kg dry weight/stere for Cerrado in Carajas (Brazil, PGC/CODEBAR/SUDAM, 1986:70).
(c) Assumes 1.12 multiplier for 0-10 cm fraction used for forest and that firewood is >10 cm diameter.
(d) Assumes underground biomass = 64% of total biomass (value used by Seiler and Crutzen, 1980:212 for "scrubland")
(e) Brazil, PGC/CODEBAR/SUDAM, 1986.
(f) Brazil, Projecto RADAMBRASIL, Vol. 26, 1982.
(g) Brazil, Projecto RADAMBRASIL, Vol. 27, 1982.

The transfer probabilities in the diagram and accompanying matrix are approximate, based on the following general observations.[3] Annual crops are usually cultivated for only two years in a cropping cycle. Of the areas cleared from forest, about 20% are planted to annual crops and 80% directly to pasture. Of farmland reaching the end of a cropping period, about 20% is allowed to revert to secondary forest and 80% is planted to pasture. Pastures last about 15 years on average before degrading either to woody secondary forest (60%) or unproductive grassland (40%). Woody secondary forest stands (*capoeira*) are cleared after an average of about ten years (they are not left for the 20-30 year fallow periods that characterize traditional shifting cultivation: see Fearnside, 1985b). Assumption of a ten year average fallow is optimistic, given that colonists in the first six years of settlement on the Transamazon Highway cleared secondary forests of two years age or less with such high frequency that ten-year fallows would be a rarity were the farmers' behavior to remain unchanged (Fearnside, 1984). "Reclaiming" of degraded grasslands to reform pastures takes place in about 10% of an area over a period of approximately 15 years (based on histories in the Paragominas area surveyed by Uhl *et al.*, 1988): this corresponds to a 75-year mean transformation time from degraded grassland to pasture. A degraded grassland would take an average of about 50 years to be transformed to secondary forest. The combination of pasture recovery and reversion to secondary forest implies a mean residence time in the "degraded pasture" category of about 30 years. After 100 years a secondary forest is considered primary forest again (from the point of view of biomass). This is conservative, given that very old secondary forest in Venezuela that did not start as degraded pasture is estimated to take 140-200 years to recover the biomass stock of primary forest (Saldarriaga *et al.*, 1986: 122).

I emphasize that several of the above values represent only informed guesses about quantities for which no quantitative data exist. Grouping land uses into only five categories (forest, farmland, productive pasture, degraded pasture and secondary forest) represents a simplification of the successional path following clearing (see Fearnside, 1990c,d), but is valuable as a first approximation. Changes in the region's rainfall regime as a result of deforestation could worsen the replacement vegetation scenario from the carbon storage point of view by favoring savannaization (Fearnside, 1985c, 1988; Shukla *et al.*, 1990).

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 of increased population pressure and increased use intensity over time has been to shorten 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 emissions. The assumption of constant transition probabilities is also optimistic because degradation of soil under pasture, combined with rainfall changes expected should the scale of deforestation greatly expand, are likely to make low-biomass dysclimaxes, including grassy formations, the dominant land cover in a deforested Amazon.


0.005
0.167
0.500
Forest
Farmland
0.833
0.400
0.100
0.010
0.930
0.042
Productive pasture
Secondary Forest
0.090
0.028
0.009
0.014
0.895
Degraded pasture
0.977

Exponentiation of the matrix of transfer probabilities 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 would contain 0.01% forest, 0.04% farmland, 35.6% productive pasture, 43.4% degraded pasture and 20.5% secondary forest (Table 15). A weighted average of the biomass of vegetation in this equilibrium landscape (27 MT/ha) is calculated in Table 16.

The above calculations only refer 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 in the forest 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 will do so over a period of about 10 years. Bacterial decomposition and termite activity will also be largely over the first decade. Soil carbon pools will change relatively quickly at the surface, but may take much longer for deeper pools (only carbon to 20 cm is considered in the current calculation). Charcoal is a very long term pool, considered to be permanently sequestered in the analysis. The carbon calculations in the present paper represent "committed carbon," or the carbon 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. To the extent that deforestation rates have remained constant, releases from the areas deforested in previous years will be equal to the future releases from the areas being cleared now. In fact, deforestation rates increased over the 1970-1987 period, and declined over the 1987-1991 period.

Char 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 2.6% of above-ground carbon being converted to char (Fearnside *et al.*, nd-d). 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 generally assume that forest is only burned 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 char formed in earlier burns can be expected to be combusted as well. A typical scenario of three reburnings over a ten-year period would raise the percentage of above-ground C converted to charcoal from 2.6% to 3.2% (Table 18), using the parameters for transformations of gross carbon stocks given in Table 17. The carbon transformations over a typical 10-year sequence are shown diagrammatically in Figure 4.

Table 15. List of parameters for transformations of gross carbon stocks

Parameter	Value	Units	Source	Comment
Total biomass	372	MT/ha dry weight	Table 13	Weighted mean for areas being cleared in 1990
Carbon content of biomass	0.5	fraction of dry weight	Brown & Lugo 1984	
Above-ground fraction	0.809		Table 8	Average at Manaus, Jari and Paragomi
Combustion efficiency in initial burn	0.275	fraction of C released	Fearnside *et al.* nd-c	Near Manaus, Amazonas
Char C fraction in initial burn	0.026		Fearnside *et al.* nd-c	Near Manaus, Amazonas
Fraction of char on biomass following initial burn	0.89		preliminary data from Fearnside *et al.* nd-d	Near Altamira, Pará
Exposed to soil char c transfer fraction during 1st interval	0.3		guess	1st interval = 4 years
Fraction surviving decay in 1st interval	0.41		Calculated from Uhl and Saldarriaga nd (a)	
Combustion efficiency in 1st reburn	0.145	fraction of C released	Preliminary data from Fearnside *et al.* nd-f	Burn in Apiau, Roraima
Fraction converted to char in 1st return	0.011		Preliminary data from Fearnside *et al.* nd-f	Burn in Apiau, Roraima (NB: includes charcoal from capoeira)
Char C combustion fraction in 1st reburn	0		Assumed zero b/c char converstion value is net	
Fraction surviving decay in 2nd interval	0.57		Calculated from Uhl and Saldarriaga nd (b)	2nd interval = 3 years
Combustion efficiency in 2nd reburn	0.011		Assumed equal to 1st reburn	
Fraction of C converted to char in 2nd reburn	0.89		Assumed equal to initial burn	
Exposed to soil char C transfer fraction during 2nd interval	0.3		guess	
Char C combusted fraction in 2nd reburn	0		Assumed zero b/c char conversion value is net	
Fraction of char on biomass after 2nd reburn	0.89		Assumed equal to initial burn	
Exposed to soil char C transfer fraction during 3rd interval	0.3		guess	
Fraction surviving decay in 3rd interval	0.77		Calculated from Uhl and Saldarriaga nd (b)	3rd interval = 3 years
Combustion efficiency in 3rd return	0.145	fraction of wood C released	Assumed equal to 1st reburn	
Fraction of C to char in 3rd reburn	0.011		Assumed equal to 1st reburn	
Char C combustion fraction in 3rd reburn	0		Assumed zero b/c char conversion value is net	
Soil C release from top 20 cm	3.92	MT/ha	Fearnside 1985a, 1987a	
Replacement vegetation biomass	27	MT/ha	Table 17	Weighted average for equilibrium land

Notes: (a) Uhl and Saldarriaga (nd) report an average of 97.3 MT of above ground dry weight biomass remaining 3-4 years after clearing a Venezuelan forest whose original above-ground biomass was believed to be 290 MT/ha based on estimates in the area by Stark and Spratt (1977). Assuming the combustion efficiency (0.275) and charcoal formation fraction (0.026) measured in Brazil (Fearnside *et al.*, nd-b), the post-burn above-ground biomass exposed to decay in Venezuela would be reduced to 200 MT/ha. Loss to decay over the 3.5 year interval (using the midpoints of the range of site ages) would therefore be 51%. Loss in a 4-year interval following the initial burn would be 59%.

(b) Uhl and Saldarriaga (nd) report average biomass as 56 MT/ha for 6-7 year-old sites; 45.3 MT/ha for 8-10 year old sites, 22.7 MT/ha for 12-20 year old sites and 7 MT/ha for 30-40 year old sites. Assuming a linear decline in wood mass within each age interval (and using midpoints of age ranges as the limits of the intervals), the loss per year as a percentage of the wood mass at the beginning of each interval would be 14.7% for 0-3.5 years, 14.2% for 3.5-6.5 years, 7.6% for 6.5-9 years, 7.2% for 9-16 years and 3.6% for 16-35 years. These loss rates have been used to calculate loss values for the intervals used in the present calculation (0-4 years, 4-7 years and 7-10 years).

Table 16. Markov matrix of transition probabilities

Initial state	Later state				
	Forest	Agriculture	Productive pasture	Degraded pasture	Secondary forest
Forest	0	0.167	0.833	0	0
Agriculture	0	0.500	0.400	0	0.100
Productive pasture	0	0	0.930	0.028	0.042
Degraded pasture	0	0	0.009	0.977	0.014
Secondary forest	0.005	0.010	0.090	0	0.895
Equilibrium proportions	0.01%	0.04%	35.6%	43.4%	20.5%

5. SOURCES AND SINKS OF GREENHOUSE GASES

5.1. Burning

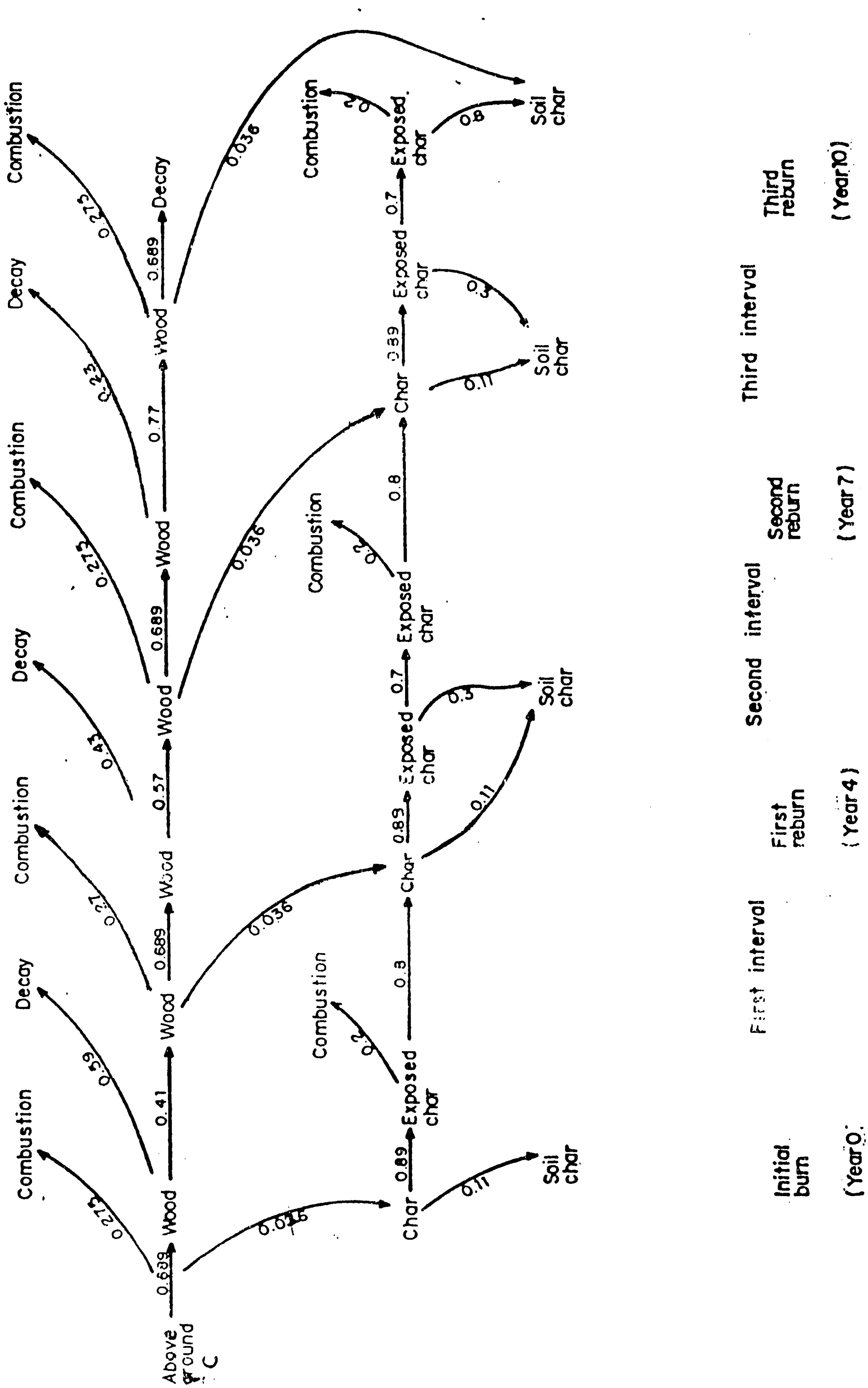
Biomass carbon not converted to charcoal is released through combustion and decay, the relative importance of each affecting the gases emitted. If an area were burned only once, 28.4% of the pre-burn above-ground carbon would be released through combustion and 69.0% through decay. With a typical scenario of three reburnings 35.0% would be released through combustion and 61.9% through decay. Both combustion and decay release other trace gases such as methane.

The parameters for carbon emissions (CO_2, CH_4 and CO) from the different burning and decay transformations of biomass are given in Table 18. Two sets of parameters are given: a "low methane" and a "high methane" scenario, reflecting the range of values appearing in the literature for releases from such sources as termites and flaming and smoldering burns. Carbon emissions as CO_2, CH_4 and CO are diagrammed in Figure 5 with parameters for the low-methane scenario. The low and high scenarios might more accurately be designated "trace gas" rather than "methane," as other gases are also included. Parameters for other sources of greenhouse gases from land-use change are given in Table 19, and trace gas release parameters are given in Table 20.

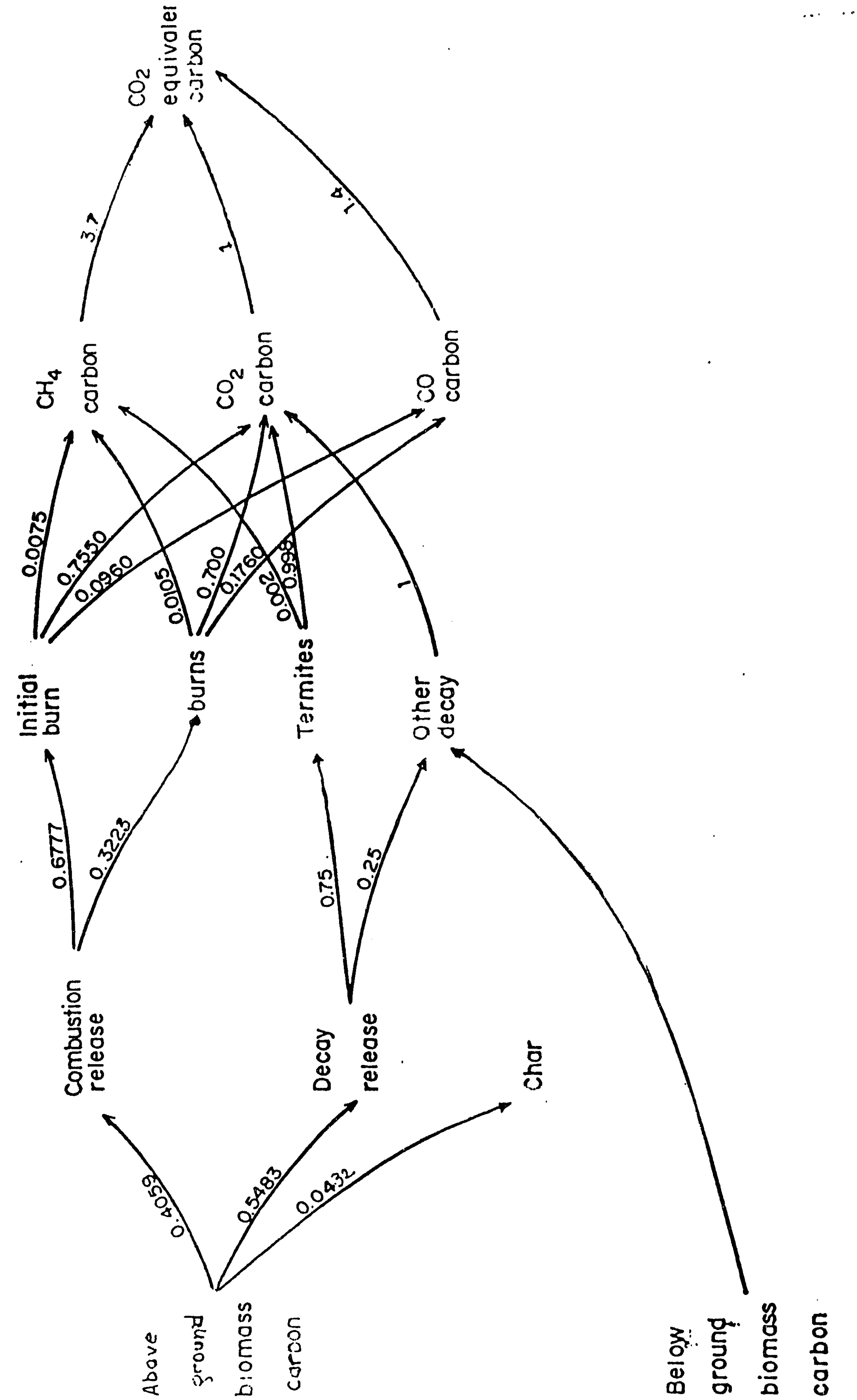
The amount of methane released is heavily dependent on the ratio of smoldering to flaming combustion; smoldering releases substantially more CH_4. Aircraft sampling over fires (mostly from virgin forest clearing) indicates that a substantial fraction of combustion is in smoldering form (Andreae *et al.*, 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, including various chlorofluorocarbons (CFCs) that provoke stratospheric ozone depletion, in addition to the greenhouse effect.

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, 1990). The parameters used in the present estimate (Table 20) are unaffected by the artifact.



Above ground C
Wood
Char
Exposed char
Soil char
Combustion
Decay
0.689
0.273
0.036
0.89
0.11
0.41
0.59
0.8
0.2
0.57
0.43
0.7
0.3
0.77
0.23
0.689
Initial burn
(Year 0)
First interval
First reburn
(Year 4)
Second interval
Second reburn
(Year 7)
Third interval
Third reburn
(Year 10)



Above ground biomass carbon
Below ground biomass carbon
Combustion release
Decay release
Char
Initial burn
burns
Termites
Other decay
CH_4 carbon
CO_2 carbon
CO carbon
CO_2 equivalent carbon
0.4059
0.5483
0.0432
0.6777
0.3223
0.75
0.25
0.0075
0.7550
0.0960
0.0105
0.700
0.1760
0.002
0.998
1
3.7
1
1.4

Table 17. Replacement vegetation weighted biomass calculation

Category	Equilibrium proportion	Biomass total (mt/ha)	Biomass source	Residence time (years)	Transition time source
Forest	0.001	394	(a)	1	(a)
Farmland	0.004	10	(b)	2	(e)
Productive pasture	0.356	10.67	(c)	15	(f)
Degraded pasture	0.434	27	(d)	30	(f)
Secondary forest	0.205	53	(d)	10	(g)
Weighted mean:		26.82			

Sources:

(a) Table 12; Secondary forest is assumed to be equivalent to original forest from the standpoint of biomass after 100 years. Saldariaga *et al.* (1986:96) calculated recovery in 144-189 years in Venezuela.
(b) guess
(c) Fearnside *et al.*, nd-d; see Fearnside, 1989e.
(d) Fearnside, 1987a
(e) general observation (see Fearnside, 1985b).
(f) based on study of large ranchers in Paragominas, Pará (Uhl *et al.*, 1988).
(g) based on study of small farmers on Transamazon Highway (Fearnside, 1984, 1986a).

Table 18. Parameters for carbon emissions

Scenario	Component	Transformation	Value (C released in this form/C present in component	MT gas released/ MT fuel burned	Basis and reference
Both high and low methane scenarios	Above-ground biomass carbon	combustion release	0.3495		Calculated from parameters in Table 15 and Figure 4.
		decay release	0.6188		Calculated from parameters in Table 15 and Figure 4.
		Charcoal carbon formation (initial+subsequent burns)	0.0318		Calculated from parameters in Table 15 and Figure 4.
	Carbon released through combustion	initial burn	0.6777		Calculated from parameters in Table 15 and Figure 4.
		reburns	0.3223		Calculated from parameters in Table 15 and Figure 4.
		Combustion release of below ground biomass	0		Assumption
	Carbon released through decay	Decay release through termites (above ground)	0.75		Based on statement by A. Bandeira that "most" of biomass is ingested
		Decay release through other decay (above ground)	0.25		Based on statement by A. Bandeira that "most" of biomass is ingested
		Decay release of below-ground biomass	1		Assumption
		Decay release through termites (below ground)	0		Assumption (unrealistically low)
		Decay release through other decay (below ground)	1		Assumption (unrealistically high)
Low methane scenario	Carbon released by combustion in initial burn	CH4 carbon	0.0075	0.005	Kaufman *et al.* 1990 from Ward 1986
		CO2 carbon	0.775	1.55	Kaufman *et al.* 1990 from Ward 1986
		CO carbon	0.096	0.12	Kaufman *et al.* 1990 from Ward 1986
	Carbon released by combustion in reburns	CH4 carbon	0.0105	0.007	Kaufman *et al.* 1990 from Ward 1986
		CO2 carbon	0.7	1.4	Kaufman *et al.* 1990 from Ward 1986
		CO carbon	0.176	0.22	Kaufman *et al.* 1990 from Ward 1986
	Carbon released through termites	CH4 carbon	0.002	0.001	Seiler *et al.* 1984 cited by Fraser *et al.* 1986
		CO2 carbon	0.998	1.996	Assumed all C not released as methane is CO_2
High methane scenario	Carbon released by combustion in initial burn	CH4 carbon	0.755	0.006	Kaufman *et al.* 1990 from Ward 1986
		CO2 carbon	0.775	1.55	Kaufman *et al.* 1990 from Ward 1986
		CO carbon	0.12	0.15	Kaufman *et al.* 1990 from Crutzen *et al.* 1985
	Carbon released by combustion in reburns	CH4 carbon	0.0165	0.011	Kaufman *et al.* 1990 from Greenberg *et al.* 1984
		CO2 carbon	0.7	1.4	Kaufman *et al.* 1990 from Ward 1986
		CO carbon	0.224	0.28	Kaufman *et al.* 1990 from Greenberg *et al.* 1984 and Ward 1986
	Carbon released through termites	CH4 carbon	0.0079	0.005	Goreau and de Mello 1987
		CO2 carbon	0.9921	1.984	Assumed all C not released as methane is CO_2

Table 19. Parameters for other sources of greenhouse gases from land-use change

Factor	Units	Value	Reference	Note
Soil carbon from top 20 cm	MT C/ha	3.92	Fearnside, 1985a	(a)
Cerrado biomass carbon	MT C/ha	32.33	Table 14	(b)
Hydroelectric dams CH4	mg CH4/m^2/day	43	Aselmann and Crutzen, 1990: 446	(c)
Cattle CH4	kg CH4/head/year	55	Ahuja, 1989	
Cattle stocking rate	head/ha	0.3	Fearnside, 1979	(d)
Pasture soil N20	kg N20/ha/year	3.8	Luizao et al, 1989	(e)

Notes: (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 MT/ha) of Cerrado with average total biomass of 45 MT/ha.

(c) Global average for lakes.

(d) Feeding capacity after 3 years.

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

Table 20. Trace gas parameters

Factor	Gases	Value	Units	Source
Intact forest soil sink	CH4	MT C/ha/yr	-0.0004	Keller *et al.* 1986
Burning release	N20 (a)(b)	MT gas/CO2 emitted from burn	0.0002	Cofer *et al.* (1988) cited by Kaufman *et al.* 1990
Burning release	N20 (c)(d)	Mt gas/MT C	0.0017	Calculated by Keller *et al.* 1991:146 from Andreae *et al.* 1988
Burning release	NOx (e)	Mt gas/MT C burned	0.0079	Keller *et al.* 1991:146
Intact forest release	NOx (e)	MT gas/ha/yr	0.0131	Kaplan *et al.* 1988; see Keller *et al.* 1991.
Flaming burn release	Total particulates	MT/MT CH4 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	MT/MT CH4 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)	MT/MT CH4 gas from burn	0.67	Derived using factor of 0.2 MT NMHC/MT particulates calculated by Kaufman *et al.* (1990:380).
Shouldering burn release	NMHC (b)	MT/MT CH4 gas from burn	0.50	Derived using factor of 0.3 MT CH4/MT particulates calculated by Kaufman *et al.* (1990:380).
Mixed burn release	NMHC (d)(f)	MT/MT C burned	0.0131	Keller *et al.* (1991:146) from measurements of Andreae *et al.* (1988).
Intact forest release	NMHC	MT gas/ha yr	0.12	Rasmussen and Khalil 1988:1420

Notes: (a) Intact forest release accounted for in pasture soil calculation.
(b) Used in low methane scenario.
(c) results in 0.088 MT gas/ha burned, or three times the 0.032 MT gas/MT C burned obtained using the parameter relating N20 to CO2.
(d) Used in high methane scenario
(e) NOx weight given NO2 basis (following Shine *et al.* 1990:61)
(f) NMHC emission corresponds to 0.69 MT gas/ha burned, much higher than values derived from methane, which are (for high and low methane scenarios, respectively): 0.21 and 0.25 MT NMHC/ha burned for flaming combustion and 0.06 and 0.09 MT NMHC/ha burned for shouldering combustion.

5.2. 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 21. The layer compacted from the top 20 cm of forest soil releases 3.92 MT/ha of carbon (the value used in the current calculations).

The 3.92 MT/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 is the low bias introduced by having considered only the top 20 cm.

If soil to one m depth is considered (the usual practice), and the same 38% of pre-conversion carbon is released, then the release would be increased to 9.33 MT/ha (Table 21). 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, 1987a). Brown and Lugo (1982: 183) have used a similar relationship to estimate carbon stocks 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.

5.3. Termites and Decay

Termites are the major agent of decay for unburned wood (Uhl and Saldarriaga, nd). 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). A lively controversy surrounds the question

Table 21. Soil carbon parameters and calculations

	Units	Value	Source
PARAMETERS			
Soil density in forest	g/cm³	0.56	Hecht 1981:95
Carbon in forest soil	% by wt.	0.91	Falesi 1976:31 & 42
Carbon in pasture soil	% by wt.	0.56	Falesi 1976:31 & 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	MT/ha	1120	
Carbon in forest soil	MT/ha	10.19	
Carbon in pasture soil compacted from top 20 cm of forest soil	MT/ha	6.27	
Release from top 20 cm	MT/ha	3.92	
Release fraction of pre-conversion soil C	% by wt.	38	
Top meter of soil:			
Soil dry weight	MT/ha	5,600	
Carbon in forest soil	MT/ha	24.27	
Carbon in pasture soil	MT/ha	14.93	
Release from top meter	MT/ha	9.33	
Release fraction of pre-conversion soil C	% by wt.	38	

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). Support for substantial emission potential from termites in deforested areas in the Amazon is provided by high population densities in fields in Pará where forest biomass remains present (Bandeira and Torres, 1985), and high methane emissions from termite mounds near Manaus (Goreau and de Mello, 1987). The low-methane scenario in the present paper assumes that 0.2% of the carbon ingested by termites is transformed into methane (Seiler *et al.*, 1984), while the high-methane scenario assumes that 0.77% of the carbon is converted to methane (calculated from Goreau and de Mello, 1987). The values of Zimmerman *et al.* (1982, 1984) are not used. The billions of metric tons of wood that these insects would devour as Amazonia is deforested cannot help producing substantial contributions of methane regardless of which production rates prove to be correct.

5.4. Cattle and Pasture

Methane is produced in the rumens of the cattle that occupy pastures in deforested areas. The portion of the area considered to be maintained under pasture is that derived from the equilibrium landscape (Tables 16 and 17). Parameters used to derive methane emissions from cattle are included in Table 19.

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 the emissions from the initial burning, conversion of a given hectare to pasture does not result a one-time release of greenhouse gas, but rather a continuous additional flux at this rate for as long as the area is maintained under this land use.

One factor not included in the calculation is the production of trace gases by the reburning of pasture and secondary forest. The combustion of logs remaining from the original forest is included. The 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 the reburnings as these gases do not enter photosynthetic reactions. Methane degrades to CO_2 after an average of 10 years (Shine *et al.*, 1990: 60), 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, but which are hoped to be included in more refined versions in the future. A number of factors not included in the present calculation are summarized in Table 22.

Table 22. Factors not considered in current calculation

Factor	Gases
Reburning pasture	CO, CH4, N20, NOx
Reburning secondary forest	CO, CH4, N20, NOx
Emissions from intact replacement vegetation	CH4, NOx, NMHC
Soil release below 20 cm	CO2
Forest degradation (logging, etc.)	CO2
Cerrado burning frequency acceleration	CO, CH4, N20, NOx
Graphitic C in soot	CO2

5.5. 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 20). 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. In the case of NMHC, the net effect of deforestation is to decrease this greenhouse gas source over the 20-year period used in the current calculation, canceling 4-5% of the impact of other emissions. The effects of removing intact forest sources are included in the parameters for trace gases (Table 20). 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.

5.6. Hydroelectric Dams

The calculations presented above consider only emissions from conversion of natural vegetation to cattle pasture -- the dominant trend in Brazilian Amazonia today. Another form of conversion with great potential impacts is construction of hydroelectric dams in rain forest areas. These release greenhouse gases both by the decomposition of the dead forest left standing in the reservoirs and by the continuing release of methane from the flooded areas (especially in the portions that are alternately dried and flooded).

Hydroelectric dams are commonly believed to have no impact on the greenhouse effect, in contrast to fossil fuel use. The validity of this conclusion, however, depends heavily on the biomass of the vegetation in the flooded areas and on the power output of the dams. In Amazonia, dams are frequently worse than petroleum from the point of view of greenhouse emissions. The worst case is the Balbina Dam, which was closed in 1987. Located on relatively flat terrain, Balbina's shallow 2360 km^2 reservoir can only generate enough power to deliver an average of 109 megawatts to Manaus (Fearnside, 1989b). The biomass of the flooded forest is now decomposing, releasing its carbon to the atmosphere. Generating the same energy from petroleum would take 250 years to equal the carbon release from flooding the Balbina reservoir (based on Junk and de Mello, 1987; see Fearnside, 1989b).

The Amazonian *várzea* (white water floodplain) has been identified as one of the world's major sources of atmospheric methane (Mooney *et al.*, 1987). The *várzea* occupies about 2% of the 5 X 10^6 km^2 Legal Amazon, the same percentage that would be flooded if all of the 100,000 km^2 of reservoirs planned for the region are created (Brazil, ELETROBRÁS, 1987: 150). Virtually all of the planned hydroelectric dams are in the forested portion of the region, of which they would represent approximately 2.5-2.9%. 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. Like biogenic release of N_2O, this would be a permanent addition to greenhouse gas sources, rather than a one-time input. The parameter for methane emissions from hydroelectric dams included in Table 19 (43 mg $CH_4/m^2/day$) is a mean for lakes of the world, and is undoubtedly conservative for the anoxic conditions that characterize the bottoms of Amazonian reservoirs like Balbina.

Measurements in natural *várzea* lakes indicate emissions ranging from 5-60 mg CH_4/m^2/day in permanent aquatic portions of the lakes free of macrophytes, to 15-200 mg CH_4/m^2/day in flooded forest (Wassmann and Thein, 1989). In 1990, no new reservoirs were filled in the Legal Amazon. The emissions can be significant, however: for reservoirs filled in 1988, 20 X 10^6 MT of CO_2-equivalent carbon were emitted (Fearnside, nd-a, using global warming potentials at 5% discount rate from Lashof and \huja, 1990).

The quantities of gases released by each source and absorbed by each sink are given in Table 23 for the low-methane scenario. Table 24 presents the corresponding results for the high methane 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.

6. GLOBAL WARMING IMPACT OF EMISSIONS

The effect of trace gases such as methane and carbon monoxide is to raise the impact of each ton of carbon released by Amazonian deforestation. Fossil fuel burning, in contrast, releases almost only CO_2. The technical uncertainties between the low and high methane scenarios have much less effect than does the policy framework used to interpret the results, which determines the time horizon of the calculation -- or, alternatively, the discount rate (Fearnside, nd-a).

The global warming potentials used in the current calculation are those derived by the Intergovernmental Panel on Climate Change (IPCC) for its 20-year scenario, including indirect effects (Shine *et al.*, 1990: 60). These are presented in Table 25. The 20-year time horizon is justified by IPCC as that reflecting the likely time period for climatic impacts on rainfall regimes in temperate regions, one of the major global consequences of global warming. The IPCC also made calculations with 100 and with 500 year time horizons. The 100-year horizon is justified as that corresponding to major changes in sea levels (Shine *et al.*, 1990: 58). The IPCC gives no justification for the 500-year horizon, and, indeed, it is difficult to explain why this calculation was made other than to direct attention to the 100-year values as a form of "middle" estimate. Although the IPCC notes that "these three different time horizons are presented as candidates for discussion and should not be considered as having any special significance" (Shine *et al.*, 1990: 59), the more extensive and graphic presentation of results from the 100-year integration, including those in the IPCC report's executive summary, tends to draw attention to this set of parameters. However, for a variety of reasons both legitimate and not, the events of the next 20 years are of much more concern to the world's population today than are events 80-100 years in the future. The longer the time horizon used in greenhouse calculations, the less the impact of short-lived but highly absorbing gases like methane that are produced by tropical deforestation.

Table 23. Greenhouse gas emissions by source for 1990 clearing in the Legal Amazon, Low Methane Scenario

Sources		Area affected (10^3 km^2)	Emissions (million MT of gas) CO2	CH4	CO	N2O	NOx	NMHC
FOREST	Initial burn	13.8	193.21	0.57	13.71	0.04	0.45	0.38
	Reburns	13.8	47.26	0.22	6.81	0.01	0.12	0.11
	Termite methane	13.8		0.36				
	Other decay	13.8	709.45					
	Cattle (a)	4.9		0.16				
	Pasture soil (a)	4.9				0.04		
	Loss of intact forest sources (a)	11.0		-0.01			-0.29	-2.63
	Soil C stock	13.8	21.67					
	Regrowth	13.8	-74.11					
	Hydroelectric (a)	0.0		0.00				
	Forest subtotal		897.47	1.29	20.52	0.09	0.28	-2.14
CERRADO	Initial burn	10.0	20.64	0.06	1.46	0.00	0.05	0.04
	Reburns	10.0	1.99	0.01	0.29	0.00	0.01	0.00
	Termites	10.0		0.04				
	Other decay	10.0	75.58					
	Cattle (a)	10.0						
	Pasture soil (a)	10.0				0.08		
	Loss of intact cerrado sources (a)(b)	10.0		-0.01			-0.02	-0.14
	Soil C stock	10.0	15.68					
	Regrowth	10.0	-21.34					
	Cerrado subtotal		92.55	0.10	1.75	0.08	0.04	-0.09
TOTAL LEGAL AMAZON			990.02	1.39	22.27	0.17	0.32	-2.24

Notes: (a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N20, hydroelectric methane) summed for 20-year period for consistency with IPCC 20-year horizon calculation.

(b) Intact cerrado source for NOx 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 MT/ha (dos Santos, 1989:194); Forest (at Tucurui, Pará) = 12.94 MT/ha (Revilla Cardenas *et al.*, 1982:6).

Table 24. Greenhouse gas emissions by source for 1990 clearing in the Legal Amazon, High Methane Scenario

Sources		Area affected (10^3 km²)	Emissions (million MT of gas) CO2	CH4	CO	N2O	NOx	NMHC
FOREST	Initial burn	13.8	193.21	0.69	17.14	0.10	0.45	0.75
	Reburns	13.8	47.26	0.34	8.66	0.03	0.12	0.20
	Termite methane	13.8		1.40				
	Other decay	13.8	706.30					
	Cattle (a)	4.9		0.16				
	Pasture soil (a)	4.9				0.04		
	Loss of intact forest sources (a)	11.0		-0.01			-0.29	-2.63
	Soil C stock	13.8	21.67					
	Regrowth	13.8	-74.11					
	Hydroelectric (a)	0.0		0.00				
	Forest subtotal		894.33	2.58	25.80	0.16	0.28	-1.68
CERRADO	Initial burn	10.0	20.64	0.07	1.83	0.01	0.05	0.08
	Reburns	10.0	1.99	0.01	0.36	0.00	0.01	0.01
	Termites	10.0		0.14				
	Other decay	10.0	70.35					
	Cattle (a)	10.0						
	Pasture soil (a)	10.0				0.08		
	Loss of intact cerrado sources (a)(b)	10.0		-0.01			-0.02	-0.14
	Soil C stock	10.0	15.68					
	Regrowth	10.0	-21.34					
	Cerrado subtotal		87.32	0.22	2.20	0.09	0.04	-0.05
TOTAL LEGAL AMAZON			981.65	2.80	28.00	0.25	0.32	-1.74

Notes: (a) Recurring effects (cattle methane, forest soil methane sink, pasture soil N20, hydroelectric methane sink, pasture soil N20, hydroelectric methane) summed for 20-year period for consistency with IPCC 20-year horizon calculation.

(b) Intact cerrado source for NOx 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 MT/ha (dos Santos, 1989:194); Forest (at Tucurui, Pará) = 12.94 MT/ha (Revilla Cardenas *et al.*, 1982:6).

Table 25. Global warming potential of trace gases

Gas	Atmospheric life (years)	Global warming potential (a) including indirect effects (per ton of gas relative to carbon dioxide)		
		20-year cutoff	100-year cutoff	500-year cutoff
CO2	120	1	1	1
CH4	10	63	21	9
CO		7	3	2
N20	150	270	290	190
NOx		150	40	14
NMHC		31	11	6
Indirect Effects included in above totals:				
Source gas	Greenhouse gas affected			
CH4	Tropospheric 03	24	8	3
CH4	CO2	3	3	3
CH4	Stratospheric H20	10	4	1
CO	Tropospheric 03	5	1	0
CO	CO2	2	2	2
NOx	Tropospheric 03	150	40	14
NMHC	Tropospheric 03	28	8	3
NMHC	CO2	3	3	3

Note: (a) Shire *et al.*, 1990:60; includes indirect effects.

Table 26. Greenhouse emissions from 1990 deforestation

Gas	GWP (a)	Low methane scenario						High methane scenario						Contribution of each gas to total effect (%)		Gross carbon					
		Amount emitted (million MT of gas/year)			CO2 equivalent (million MT of gas/year)			Amount emitted (million MT of gas/year)			CO2 equivalent (mil. MT of gas/yr)					Forest		Cerr.		Total	
		Forest	Cerr.	Total	Forest	Cerr.	Total	Forest	Cerr.	Total	Forest	Cerr.	Total	LMS	HMS	LMS	HMS	LMS	HMS	LMS	HMS
CO2	1	897.47	92.55	990.02	897.47	92.55	990.02	894.33	87.32	981.65	894.33	87.32	981.65	78.7	69.4	244.77	243.91	25.24	23.81	270.01	267.72
CH4	63	1.29	0.10	1.39	81.51	6.13	87.64	2.58	0.22	2.80	162.53	13.65	176.18	7.0	12.5	0.97	1.93	0.07	0.16	1.04	2.10
CO	7	20.52	1.75	22.27	143.63	12.26	155.89	25.80	2.20	28.00	180.62	15.37	195.99	12.4	13.9	8.79	11.06	0.75	0.94	9.54	12.00
N2O	270	0.09	0.08	0.17	23.08	21.74	44.82	0.16	0.09	0.25	42.95	23.58	66.53	3.6	4.7						
NOx	150	0.28	0.04	0.32	42.62	5.68	48.30	0.28	0.04	0.32	42.62	5.68	48.30	3.8	3.4						
NMHC	31	-2.14	-0.09	-2.24	-66.46	-2.94	-69.41	-1.68	-0.05	-1.74	-52.22	-1.61	-53.83	-5.5	-3.8						
Total CO2-equivalent gas (million MT)					1122	135	1257				1271	144	1415	100.0	100.0	254.53	256.90	26.06	24.92	280.59	281.82
C02-equivalent carbon (million MT)					306	37	343				347	39	386								

Note: a) IPCC 20-year values, including indirect effects, expressed as kg of CO2 gas equivalent/kg of gas (Table 25).

The IPCC is currently in the process of revising its approach to deriving equivalents for each gas in terms of CO_2. A series of integrations will allow allocation of responsibility for the past emissions of each country. However, the greater radiative forcing and broader absorption spectrum of CH_4 as compared to CO_2 will undoubtedly maintain the greater relative impact of carbon in the form of methane under the revised criteria.

The choice of the 20-year horizon gives more emphasis to trace gases than does the 5% annual discount rate used by US-Environmental Protection Agency (EPA) (Lashof and Ahuja, 1990), which has been used in previous calculations of the impact of Amazonian deforestation (Fearnside, nd-a). The 5% discount rate is roughly equivalent to the 30-year horizon used by the World Bank (Arrhenius and Waltz, 1990).

The emissions of each gas under the high and low methane scenarios are shown in Table 26, together with the CO_2 carbon equivalent using the 20-year horizon global warming potentials. Gross carbon releases are also shown. The effect of trace gases raises impact from the gross carbon total of 281-282 X 10^6 MT/year to the CO_2 equivalent total of 343-386 X 10^6 MT/year, an increase of 62-104 X 10^6 MT/year or 22-37%.

7. BRAZIL'S CONTRIBUTION TO GLOBAL WARMING

Global carbon emissions from deforestation are uncertain, in part because of the uncertainty associated with Brazil's large contribution to the total. One study (Houghton, 1989: 60), using the deforestation estimates of Myers (1989), estimates that Brazil contributes 0.454 GT (32.1%) of a global total of 1.398 GT of carbon released from deforestation. Using instead the comparable figure of 0.281-0.282 GT/year for gross carbon release estimated for Brazil in the present paper (Table 26), and a deforestation total of 1.402-1.413 GT/year (Tables 28-29) based on the more conservative clearing rate estimates presented in Table 27, Brazil's contribution represents 20% of the deforestation total. Deforestation in the Brazilian Amazon contributes 4.2% of the combined gross carbon total from fossil fuels and tropical deforestation. Using the fossil fuel release as the standard of comparison, as is the usual practice, Brazil's annual rate of deforestation in Amazonia represents 5.3%. Using the CO_2 equivalent carbon release of 0.343-0.386 GT (for the low and high methane scenarios), the contribution represents 4.9-5.4% of the combined deforestation and fossil fuel total or 6.5-7.3% of the global fossil fuel total (Table 30, assuming the low and high methane scenarios described here for the Brazilian Amazon apply to the non-Brazilian deforestation estimated in Tables 27-29). Tropical deforestation's contribution to total (deforestation+fossil fuel) greenhouse emissions represents 20.9-21.1% for the low and high methane scenarios in terms of gross carbon, and 24.3-26.5% in terms of CO_2-equivalent carbon (Table 30).

8. DEFORESTATION AND GREENHOUSE POLICY

Deforestation in Brazilian Amazonia already makes a significant contribution to the greenhouse effect, and continuation of deforestation trends could lead to an even greater potential contribution to this global problem. Uncertainties concerning clearing rate, biomass and other factors do not change this basic conclusion regarding the significance of deforestation.

Brazil emits 50 X 10^6 MT of carbon annually from burning fossil fuels at 1987 levels (Graça and Ketoff, nd; see also Flavin, 1989: 26). This contribution to the greenhouse effect is balanced against the benefits of the country's industry and transportation powered by oil and coal, all domestic use of natural gas, etc. In contrast, each year's clearing of forest and *cerrado* in the Brazilian Amazon is now contributing to the atmosphere 281-282 X 10^6 MT of gross carbon -- over five times as much as Brazil's use of fossil fuels (Table 30). Correction for the relative impact of trace gases releases increases the global warming stemming from deforestation to 343-386 X 106 MT, or 7-8 times Brazil's fossil fuel emissions. The benefits of deforestation, however, are minimal: it leaves in its wake only destroyed rain forests and degraded cattle pastures.

The contrast between costs and benefits of biomass burning and fossil fuel combustion are also tremendous on a per-capita basis. Discussing greenhouse emissions in terms of the per-capita average for rural Amazonia as a whole does a great injustice to the poor small farmers who make up the majority of the population. This is because most of the deforestation is done by a tiny minority of large ranches. For example, a single rancher who clears 2,000 ha of forest (with an average biomass of 372 MT/ha, releasing 221-251 MT/ha of $C \sim O_2$-equivalent C) is emitting as much carbon as a city of over 1 million people burning fossil fuels (calculation patterned after I.F. Brown, 1988).

Reliable data are not available on how much of the clearing is taking place on large ranches as opposed to small holdings. Even a very rough estimate is better, however, than the alternative of assuming that the 13.8 X 10^3 km^2 of 1990 deforestation was divided evenly among the region's approximately 8 X 10^6 rural residents. The distribution of 1990 clearing among the region's nine states (Table 2) indicates well over half in states that are dominated by large ranchers: 29% was in Mato Grosso, 35.5% in Pará (especially southern Pará where large ranchers predominate). By contrast, Rondônia -- a state that has become famous for its deforestation by small farmers -- had only 12.1% of the total, and Acre had 4%. Recognizing that predominantly small-farmer states also have large ranchers, and *vice versa*, an estimate of approximately 60-70% of the clearing being the work of large ranchers appears reasonable. At the time of the 1985 agricultural census, 1.7% of the rural establishments covered by the census had areas of 1000 ha or more, but these accounted for 62.3% of the total area of private property in the region (calculated from Brazil, IBGE, 1989: 297, considering half of the areas reported for Maranhão and Goiás to be within the Legal Amazon). The 1985 agricultural census information (Table 31) has been used in Table 32 for apportioning the 1990 emissions (remembering that the deforestation rate in 1990 was lower than that in 1985). Comparisons of per-capita emissions are shown for different property sizes and for the rural Amazonian population, Brazil as a whole, the United States and the world. It is apparent that the emissions from a tiny population of ranchers dominates the statistics not only for Amazonia but for Brazil as a whole.

The gulf between the costs and benefits of deforestation compared to fossil fuel use makes slowing forest loss an obvious place for Brazil to start reducing its contribution to global warming. The world's 400 X 10^6 automobiles release 550 X 10^6 MT of carbon annually (Flavin, 1989: 35); the 343-386 X 10^6 MT of CO_2-equivalent carbon released by Brazil's 1990 deforestation in Amazonia is therefore equivalent to the 367 X 10^3 MT reduction that could be achieved by tripling the fuel efficiency of all the cars in the world. Other nations searching for ways to best apply their funds to reduce global warming would be wise to contribute financially to helping Brazil reduce its forest loss.

Slowing forest loss is possible because the process of deforestation in Brazil is largely driven by factors that are subject to government decisions. Separate discussions have been published treating deforestation's causes in Brazil (Fearnside, 1987b), its meager benefits (Fearnside, 1985b, 1986a), heavy environmental costs (Fearnside, 1985c, 1988), and irrationality from the perspective of the long-term interests of the country (Fearnside, 1989c,d). Measures that would help slow forest loss in Brazilian Amazonia have been reviewed both from the perspective of what the Brazilian government could do (Fearnside, 1989e) and that of possible contributions from other countries (Fearnside, 1990e). It cannot be overemphasized that slowing deforestation in Brazil is in Brazil's own best interest independent of its implications for global warming: even if deforestation were beneficial from a greenhouse standpoint, Brazil would be foolish to continue clearing its Amazonian forests.

The contrast between costs and benefits of the biomass burning and the combustion of fossil fuels are also tremendous on a per capita basis. Discussing greenhouse emissions in terms of the per capita average for rural Amazonia as a whole does a great injustice to the poor small farmers who make up the majority of the population. Most of the deforestation is done by a tiny minority of large ranches. For example, a single rancher who clears 2,000 ha of forest (with an average biomass of 372 t/ha) is emitting as much carbon as a city of almost 1 million people burning fossil fuels (calculation patterned after I.F. Brown 1988).

Reliable data are not available on how much of the clearing is taking place on large ranches as opposed to small holdings. Even a very rough estimate is better, however, than the alternative of assuming that the 13.8 x 10^3 km^2 of 1990 deforestation was divided evenly among the region's approximately 8 x 10^6 rural residents. The distribution of 1990 clearings among the region's nine states (Table 2) indicates well over half in states that are dominated by large ranchers: 29 percent was in Mato Grosso and 35.5 percent in Pará (especially southern Pará where large ranchers predominate). In contrast, Rondônia -- a state that has become famous for its deforestation by small farmers -- had only 12.1 percent of the total, and Acre had 4 percent. Recognizing that predominantly small-farmer states also have large ranchers, and vice versa, an estimate of approximately 60-70 percent of the clearing being the work of large ranchers appears reasonable. At the time of the 1985 agricultural census, 1.7 percent of the rural establishments had areas of 1000 ha or more, but these accounted for 62.3 percent of the total area of private property in the region (calculated from Brazil, IBGE 1989, 297, considering half of the areas reported for Maranhão and Goiás to be within the Legal Amazon). The 1985 agricultural census information (Table 31) has been used in Table 32 for apportioning the 1990 emissions (remembering that the deforestation rate in 1990 was lower than that in 1985). Comparisons of per capita emissions are shown for different property sizes and for the rural Amazonian population, Brazil as a whole, the United States and the world. It is apparent that the emissions from a tiny population of ranchers dominates the statistics not only for Amazonia but for Brazil as a whole.

The gulf between the costs and benefits of deforestation compared to fossil fuel use makes slowing forest loss an obvious place for Brazil to start reducing its contribution to global warming. The world's 400 x 10^6 automobiles release 550 x 10^6 t of carbon annually (Flavin 1989, 35); the 346-376 x 10^6 t of CO_2-equivalent carbon released by Brazil's 1990 deforestation in Amazonia is therefore equivalent to the 367 x 10^3 t reduction that could be achieved by tripling the fuel efficiency of all the cars in the world. Other nations searching for ways to best apply their funds to reduce global warming would be wise to contribute financially to helping Brazil reduce its forest loss.

Table 27. Deforestation rates in countries with tropical moist forests[a]

Country	Deforestation (1000 ha/yr)		
	All forests (most recent estimate)	Closed forests (approximate rate)	Open forests (approximate rate)
TROPICS TOTAL	12048	8828	3637
AFRICA	3131	1888.2	1242.8
Benin	67	1.0	66.0
Burundi	1	1.0	0.0
Cameroon	190	138.2	51.8
Central African Rep.	55	5.0	50.0
Congo	22	22.0	0.0
Cote d'Ivoire	510	290.0	220.0
Gabon	15	15.0	0.0
Gambia, the	5	2.0	3.0
Ghana	72	22.0	50.0
Liberia	46	46.0	0.0
Madagascar	156	150.0	6.0
Nigeria	400	300.0	100.0
Rwanda	5	3.0	2.0
Sierra Leone	6	6.0	0.0
Togo	12	2.0	10.0
Uganda	1199	703.0	496.0
Zaire	370	182.0	188.0
CENTRAL AMERICA	1404	963.0	32.5
Belize	9	9.0	0.0
Costa Rica	42	42.0	0.0
Cuba	2	2.0	0.0
Dominican Rep.	4	4.0	0.0
El Salvador	5	5.0	0.0
Guatemala	90	90.0	0.0
Haiti	2	2.0	0.0
Honduras	90	90.0	0.0
Jamaica	2	2.0	0.0
Mexico[b]	700	668.0	32.5
Nicaragua	121	121.0	0.0
Panama	36	36.0	0.0
Trinidad & Tobago	1	1.0	0.0

(continued on following page)

Table 27 (continued). Deforestation rates in countries with tropical moist forests

Country	Deforestation (1000 ha/yr)		
	All forests (most recent estimate)	Closed forests (approximate rate)	Open forests (approximate rate)
SOUTH AMERICA	4673	3285.3	2212.2
Bolivia	117	87.0	30.0
Brazil[c]	2380	1380.0	1824.5
Colombia	890	820.0	70.0
Ecuador	340	340.0	0.0
Guyana	3	2.0	1.0
Paraguay	450	403.3	46.7
Peru	245	125.0	120.0
Suriname	3	3.0	0.0
Venezuela	245	125.0	120.0
ASIA	2814	2666.0	148.0
India	48	48.0	0.0
Indonesia	1000	967.7	32.3
Kampuchea, Dem.	30	25.0	5.0
Lao Peoples Dem. Rep.	130	100.0	30.0
Malaysia	270	270.0	0.0
Myanmar	600	600.0	0.0
Nepal	84	84.0	0.0
Pakistan	9	7.0	2.0
Philippines	150	150.0	0.0
Singapore			
Sri Lanka	58	58.0	0.0
Thailand	235	156.3	78.7
Vietnam	200	200.0	0.0
OCEANIA	26	25.0	1.0
Australia			
Fiji	2	2.0	0.0
Papua New Guinea	23	22.0	1.0
Solomon Islands	1	1.0	0.0

Notes: (a) All data from *World Resources Report 1991* (WRI, nd), except for those for Mexico and Brazil. Apportioning between open and closed forests is approximate, based on percentage of existing forests of each type listed in WRI report, aside for Brazil and Mexico.
(b) Mexico data for closed forests from Masera *et al* 1992. WRI (nd) gives 957.5 x 10^6 ha/yr as closed forest rate in Mexico.
(c) The Brazil rate considers Amazon forests as closed and Cerrado as open (rates as used in this paper).

Table 28. Rough calculation of biomass of tropical forests presently being cleared outside of Brazil

Continent	Closed forests										Open forests	
	Percent disturbed (a)	Biomass carbon if disturbed (MT C/ha) (b)	Biomass carbon if undisturbed (MT C/ha) (b)	Biomass carbon weighted average (MT C/ha)	Adjustments to Brown & Lugo above-ground estimates (c)	Carbon content of biomass (d)	Above-ground biomass (MT/ha)	Below-ground factor (root/shoot) (d)	Below-ground biomass (MT/ha)	Total biomass (MT/ha)	Biomass carbon (MT C/ha) (e)	Total biomass (MT/ha)
America	15	89	73	75	1.394	1	210.24	0.175	36.70	246.94	27	54
Africa	41	136	111	121	1.394	1	338.09	0.175	59.02	397.11	15	30
Asia	42	112	60	82	1.394	1	228.20	0.175	39:84	268.04	40	80

Sources:

(a) Used by Houghton, 1991:101, based on N. Myers, pers. comm., 1991.
(b) Used by Houghton, 1991:101, based on Brown *et al.*, 1989 (NB: refers to above-ground live biomass for trees > 10 cm DBH in original source).
(c) Fearnside, 1992.
(d) Value used for Brazil in the present study (see text).
(e) Value used by Houghton, 1991:101 based on Brown and Lugo, 1984 (NB: refers to total biomass in original source).

Table 29. Rough calculation of global greenhouse emissions from tropical deforestation

Location	Closed forests				Open forests				All forests	
	Rate of clearing (1000 ha/yr)	Biomass (above + below ground) (MT/ha)	Emissions		Rate of clearing (1000 ha/yr)	Biomass (above + below ground) (MT/ha)	Emissions		Emissions	
			(million MT gross carbon)	(million MT CO2-equivalent carbon)			(million MT gross carbon)	(million MT CO2-equivalent carbon)	(million MT gross carbon)	(million MT CO2-equivalent carbon)
LOW METHANE										
Brazil	1382	372	255	306	1000	45	26	37	281	343
Rest of America	2868	247	351	422	420	54	13	19	364	440
Africa	1888	397	372	447	1243	30	21	30	393	477
Asia & Oceania	2691	268	357	430	149	80	7	10	364	439
Total	8829		1334	1604	2812		68	96	1402	1700
HIGH METHANE										
Brazil	1382	372	257	347	1000	45	25	39	282	386
Rest of America	2868	247	354	478	420	54	13	19	367	496
Africa	1888	397	375	506	1243	30	21	30	397	536
Asia & Oceana	2691	268	361	487	149	80	7	10	368	496
Total	8829		1347	1817	2812		66	98	1413	1915

Table 30. Contribution of deforestation in Brazilian Amazonia to global greenhouse emissions

REGION	Source	GROSS CARBON				CO2-EQUIVALENT CARBON			
		Low methane scenario		High methane scenario		Low methane scenario		High methane scenario	
		Million MT	% of global total	Million MT	% of global total	Million MT	% of global total	Million MT	% of global total
BRAZIL									
	Deforestation	281	4.2	282	4.2	343	4.9	386	5.3
	fossil fuel	50	0.7	50	0.7	50	0.7	50	0.7
	Total	331	4.9	332	4.9	393	5.6	436	6.0
WORLD									
	Deforestation	1402	20.9	1413	21.1	1700	24.3	1915	26.5
	fossil fuel	5300	79.1	5300	78.9	5300	75.7	5300	73.5
	Total	6702	100.0	6713	100.0	7000	100.0	7215	100.0

Table 31. Land tenure distribution the Brazilian Legal Amazon in 1985 (a)

State	Number of establishments					Percent of area			Percent of establishments		
	< 100 ha	100-1000 ha	> 1000 ha	100-1000 ha	> 1000 ha	< 100 ha	100-1000 ha	> 1000 ha	< 100 ha	100-1000 ha	> 1000 ha
Rondônia	65,469	15,581	474	2,168	1,800	34.8	35.6	29.6	80.3	19.1	0.6
Acre	21,026	13,966	323	2,527	2,417	16.6	42.6	40.8	59.5	39.5	0.9
Amazonas	107,454	8,798	557	1,818	2,462	28.3	30.5	41.3	92.0	7.5	0.5
Roraima	2,913	2,936	574	490	1,521	6.8	22.7	70.5	45.4	45.7	8.9
Pará	215,020	36,505	2,418	6,269	12,393	20.7	26.6	52.7	84.7	14.4	1.0
Amapá	3,027	1,683	122	288	853	5.7	23.8	70.5	62.6	34.8	2.5
Maranhao (b)	252,171	11,448	1,155	5,945	3,168	14.3	55.9	29.8	95.2	4.3	0.4
Goiás (Tocantins) (b)	52,659	32,270	4,684	9,867	24,238	5.0	27.5	67.5	58.8	36.0	5.2
Mato Grosso	55,403	17,331	5,575	5,047	31,699	3.2	13.3	83.5	70.7	22.1	7.1
Legal Amazon	775,142	140,517	15,882	34,418	80,551	11.1	26.6	62.3	83.2	6.0	1.7

Notes: (a) Data from 1985 agricultural census: Brazil, IBGE, 1989: 297.
(b) For Maranhao and Goiás half of the properties are assumed to be in the Legal Amazon. The state of Tocantins was created from the northern half of Goiás in 1988, roughly the portion in the Legal Amazon.

Table 32. Greenhouse impact per capita

Source	Population (millions)	Low methane scenario			High methane scenario		
		Annual Emission (million MT CO2 equiv. C) (b)	Annual Emission per capita (MT CO2 equiv.C)	Number of people needed to equal one large rancher	Annual Emission (million MT CO2 equiv.C) (b)	Annual Emission per capita (MT CO2 equiv.C)	Number of people needed to equal one large rancher
Brazil:							
Large rancher population Amazonia (a)	0.1	213	1565.1	1	240	1761.3	1
Medium-sized rancher population of Amazonia (a)	0.5	91	190.0	8	103	213.8	8
Small farmer population of Amazonia (a)	6.7	38	5.7	273	43	6.5	273
Rural Amazonia total	8	343	51.5	30	386	48.2	37
Rest of Brazil	132	47	0.4	4396	47	0.4	4947
Brazil total	140	393	2.8	558	436	3.1	566
World	5300	7000	1.3	1185	7215	1.4	1294
United States	210	1060	5.0	310	1060	5.0	349

Notes: (a) "Large ranches" are > 1,000 ha in area, "middle-sized ranches" are 100-1000 ha in area, "small farms" are < 100 ha in area. The 1990 rural population is apportioned between these categories in proportion to the number of establishments censused in 1985 (Table 31).
(b) Emissions are allocated among property classes in proportion to the area of the establishments.

NOTES

(1) Some inconsistency remains in the definition of original forest area used here (Tables 4 and 5), and that used in the deforestation estimate (Tables 1-2). The deforestation estimate used a line between forest and non-forest drawn by INPE from LANDSAT-TM 1:250,000 scale images with some reference to the RADAMBRASIL vegetation maps (but without a list of the vegetation types classified as forest and non-forest). 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 non-forest in each sheet. The total from this compilation is 4.0×10^6 km^2, lower than the 4.3×10^6 km^2 measured from the IBDF/IBGE 1.5,000,000 scale map.

The "present" vegetation is also inconsistent: the IBDF/IBGE mapping totals 3.7×10^6 km^2 of forest (circa 1988)(Table 5), whereas the original forest area from the same map, less the area deforested by 1988 (Table 1), yields a total of 3.9×10^6 km^2.

(2) Tocantins is a state created by Brazil's October 1988 constitution from the northern half of the former state of Goiás. The border between Tocantins and the present state of Goiás is an irregular line zig-zagging along the 13th parallel S. latitude, which had previously been the limit of the "Legal Amazon" in this area. The present state of Tocantins now defines the limit of Legal Amazonia here. Deforestation data from previous years have been re-interpreted to conform to the new definition, but the areas of the vegetation types have not yet been adjusted (referred to in the tables as "Tocantins/Goiás"). Of the present state of Goiás, 2875 km^2 lies north of 13° S. Latitude, and 7411 km^2 of Tocantins lies south of this parallel (Fearnside *et al.*, nd-a). Virtually none of this area was originally forested.

(3) Annual transition probability can be obtained from the mean time to transition by calculating the number of years needed for the cumulative probability of the event (transition) occurring at least once to reach 0.5, i.e., $0.5 = (1 - P)^t$, or $P = 1 - 0.5^{1/t}$, where "P" is the annual probability of transition and "t" is the mean time to transition in years.

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