BIOMASS OF BRAZIL'S AMAZONIAN FORESTS

Philip M. Fearnside
National Institute for Research
in the Amazon (INPA)
C.P. 478
69011-970 Manaus, Amazonas
BRAZIL

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ABSTRACT

In Brazilian Amazonia the average total biomass (including dead and below-ground components) in unlogged original forests (i.e., never cleared by recent non-indigenous farmers or ranchers) is estimated to be 428 metric tons per hectare (t/ha) of dry matter (50% of which is carbon). The estimates presented here are derived from published wood volume data from 2954 ha of forest inventory surveys distributed throughout the region. These forest biomass estimates are higher than those that have been used in many global carbon calculations, including those adopted by the 1992 supplementary report of the Intergovernmental Panel for Climate Change (IPCC). The principal explanations for the lower values commonly used are omission of a number of biomass components and inappropriate conversion factors for deriving biomass from forest inventory data. The current estimate, in addition to being based on conversion factors derived from measurements in the region, is founded on a set of forest inventory data that is both much larger and spatially better distributed than any previously available.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION

The initial biomass of the vegetation is an important factor affecting the magnitude of greenhouse gas emissions from deforestation. The biomass estimates in the present paper are based on much more data than earlier estimates. The estimates for the most important forest types are higher by a factor of two than the 155.1 t/ha value for total biomass derived by Brown and Lugo (1984) from FAO forest volume surveys for "tropical American undisturbed productive broadleafed forests." The Intergovernmental Panel on Climate Change (IPCC) 1992 supplementary report (Watson et al., 1992, p. 33) opted not to revise the land-use change emission estimate of 1.6 gigatons (Gt = 10^9 t) carbon (C)/yr derived in the IPCC's 1990 scientific assessment (Watson et al., 1990, p. 17). The IPCC estimate of tropical deforestation emissions is the midpoint of the 0.6-2.5 Gt C/yr range of values for emissions in 1980 reported by Detwiler and Hall (1988) and by Houghton et al. (1985, 1987, 1988) (Watson et al., 1990, p. 11). The emissions estimate used by the IPCC for the low end of the range was made by Detwiler and Hall (1988) using the forest biomass estimates of Brown and Lugo (1984). Brown and Lugo have themselves abandoned their 1984 estimate, revising it upwards in subsequent studies (Brown et al., 1989, Brown and Lugo, 1992a,b). The high end of the IPCC's range was taken from a calculation made using an estimate of total biomass of tropical American closed forests equivalent to 352 t/ha (Houghton et al., 1987, p. 134) which these authors derived from Brown and Lugo (1982). The present paper indicates that Brazil's Amazon forests have higher biomass than was estimated in any of these studies.

Higher biomass implies greater emissions of greenhouse gases from deforestation. The studies on which the IPCC based its estimate used deforestation rates referring to 1980. The Brazilian portion of the global deforestation rate estimate acts to reduce the range, as the "low" emissions estimate used a higher rate than that used in the "high" estimate. The low emissions estimate (Detwiler and Hall, 1988, p. 43) used a deforestation rate from Seiler and Crutzen (1980, p. 223), who had estimated a minimum of 25 X 10^3 km^2/year of clearing in virgin Amazonian forests. The high emissions estimate (Houghton et al., 1987, p. 126) used a value of 17 X 10^3 km^2/year for the forests of Brazilian Amazonia, derived from Fearnside (1984) with adjustments for <u>cerrado</u> savannas (based on Brazil, IBGE, 1979, p. 42). The 17 X 10^3 km^2/year value used by Houghton et al. (1987) is probably quite close to the true value for the forest clearing rate in 1980. The annual rate of deforestation in Brazilian Amazonia increased from 1980 to 1987, averaging 20 X 10^3 km^2/year over the 1978-1988 period (Fearnside, 1993a), and then declined to 11 X 10^3 km^2/year over the 1987-1991 period, mostly due to Brazil's economic recession (Fearnside, 1993b). It is important not only that greenhouse gas emission estimates be as close as possible to the true values of these quantities, but also that they be correct for the right reasons.

Biomass of Amazonian forests has been the subject of an extended controversy, summarized in Table 1. The reported biomass values (in the first column of the table) often hide inconsistencies in the items included, such as below-ground and dead components. The second column adjusts for these inconsistencies, giving the total biomass equivalent. Values refer to a variety of different categories, such as all forests in the region, forests cleared in 1990, and forests with or without the effects of logging. Figure 1 plots the adjusted values for total biomass of all unlogged forests in the region. The first two values by Brown and Lugo are those that provide the basis for the emissions range used by the IPCC. The first value (Brown and Lugo, 1982) is based on destructive sampling, while the second (Brown and Lugo, 1984) is based on forest volumes. Brown and Lugo (e.g., 1992a,b; Lugo and Brown, 1986) have long claimed that the reason that destructive sampling consistently produces values higher than their volume-based estimates is that field ecologists are biased in their selection of unrepresentatively dense or pristine study sites. The volume-based estimates in the present paper, however, are in good agreement with existing destructive results, and indicate that the lower results from Brown and Lugo's volume-based studies stem mainly from errors and omissions in the conversion of forest inventory data to biomass.

(Figure 1 and Table 1 here)

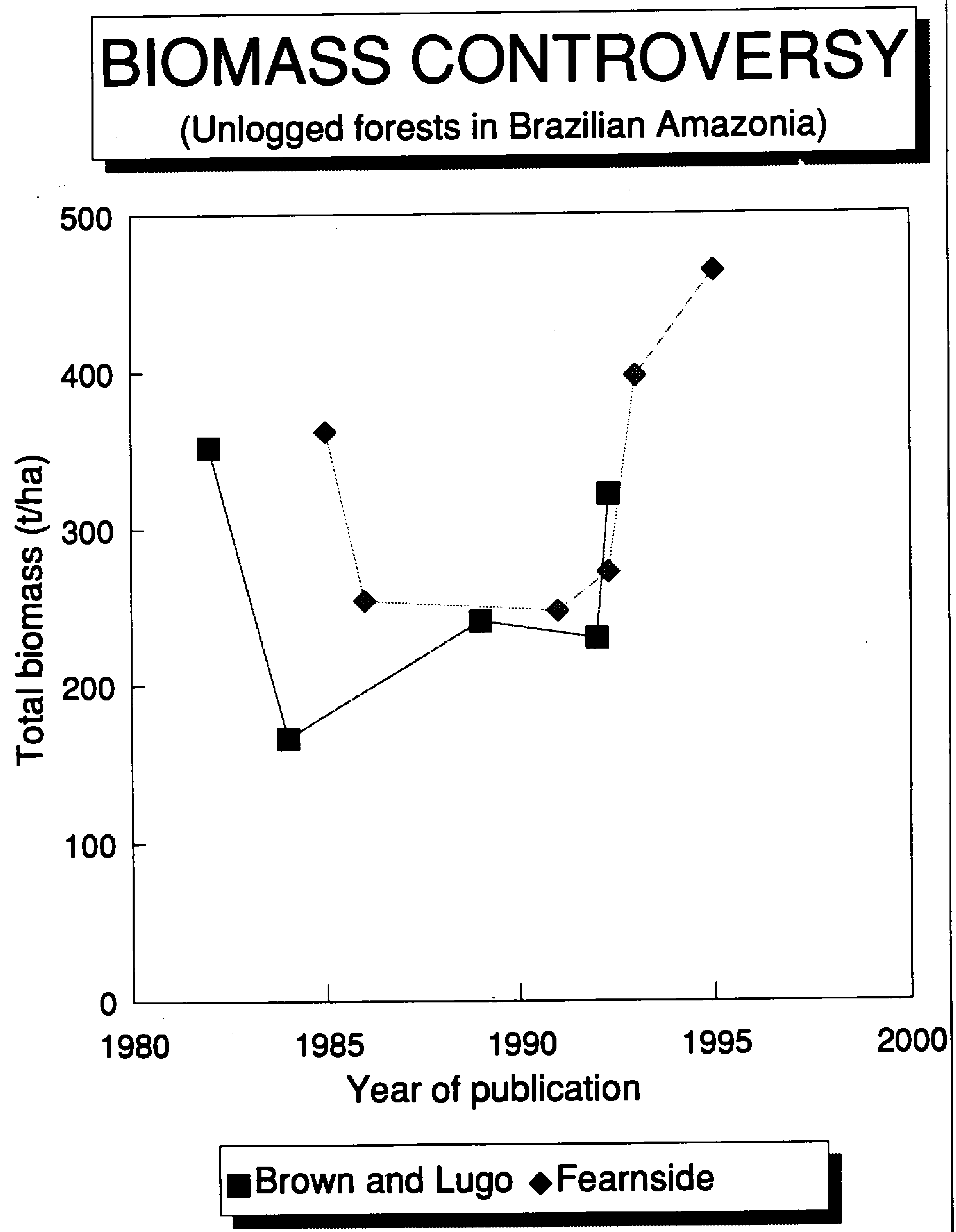

BIOMASS CONTROVERSY
(Unlogged forests in Brazilian Amazonia)
500
400
300
200
100
0
Total biomass (t/ha)
1980
1985
1990
1995
2000
Year of publication
Brown and Lugo
Fearnside

TABLE 1: AMAZON FOREST BIOMASS CONTROVERSY

Biomass reported (t/ha)	Total biomass equivalent (including components omitted in published value) (t/ha)	Source
352	352	Brown and Lugo 1982 (calculated by Houghton et al. 1987: 134)
155.1	166	Brown and Lugo 1984
362	362	Fearnside 1985
254	254	Fearnside 1986, 1987
169.68	241	Brown et al. 1989
247(a) / 211(b)	247(a) / 211(b)	Fearnside 1991
162(c,e) / 268(d,e)	230(c,e) / 380(d,e)	Brown and Lugo 1992a
227(c,e) / 289(d,e)	322(c,e) / 410(d,e)	Brown and Lugo 1992b
272(a) / 320(e)	272(a) / 320(e)	Fearnside 1992
397(a) / 375(f)	397(a) / 375(f)	Fearnside et al. 1993
428(a)	428(a)	This estimate

(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.

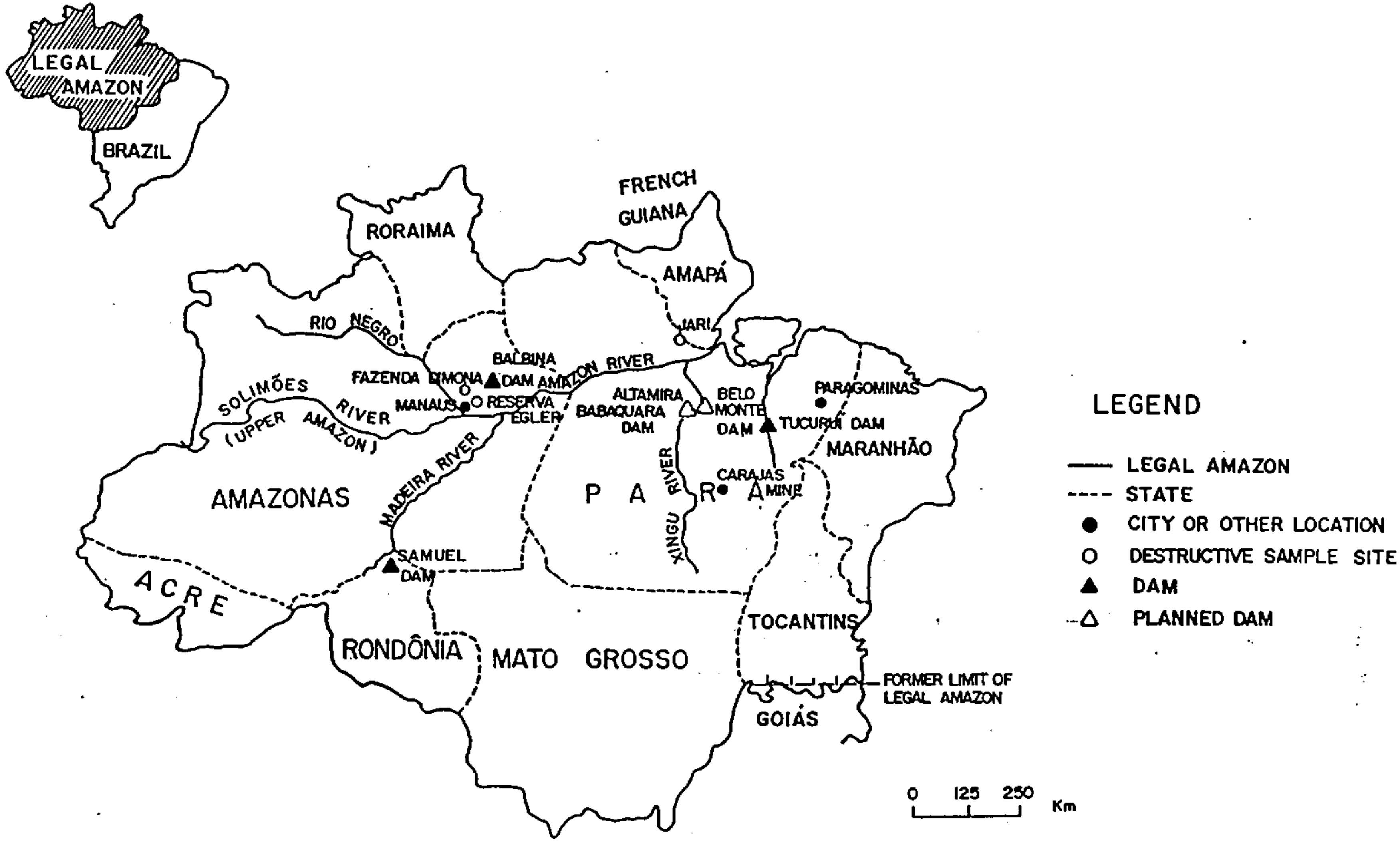
BIOMASS OF AMAZONIAN FORESTS

Vegetation types in Amazonia

Brazil's Legal Amazon region covers an area of 5 X 10^6 km^2--equivalent to about two-thirds the area of the continental United States or the entire area of western Europe (Figure 2). The different types of original vegetation present in the Legal Amazon are summarized in Table 2 and the area of each is given by state in Table 3. These areas have been measured (Fearnside and Ferraz, 1995) from a digitized version of the 1:5,000,000 scale vegetation map of Brazil published by the Brazilian Institute for Geography and Statistics (IBGE) and the Brazilian Institute for Forestry Development (IBDF--since incorporated into the Brazilian Institute for the Environment and Renewable Natural Resources - IBAMA) (Brazil, IBGE/IBDF, 1988). The IBGE/IBDF (IBAMA) map code used indicates 28 vegetation types within the Brazilian Legal Amazon, of which 19 are considered here to be forest. This is a liberal definition of forest, including all ecotones between a forest and a nonforest vegetation type such as cerrado. Cerrados are the dry scrub savannas of the central Brazilian plateau that interdigitate with the southern boundary of the forest, especially in the states of Mato Grosso, Tocantins[(1)] and Maranhão. 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 3.8 X 10^6 km^2. The areas that were originally forest and nonforest using this definition are mapped in Figure 3.

(Figures 2 and 3 here)

(Tables 2 and 3 here)


LEGAL AMAZON
BRAZIL
FRENCH GUIANA
RORAIMA
AMAPÁ
JARI
RIO NEGRO
BALBINA DAM
AMAZON RIVER
FAZENDA DIMONA
SOLIMÕES RIVER
(UPPER AMAZON)
MANAUS
RESERVA EGLER
ALTAMIRA
BABAQUARA DAM
BELO MONTE DAM
PARAGOMINAS
TUCURUI DAM
MARANHÃO
MADEIRA RIVER
XINGU RIVER
CARAJAS MINE
P A R Á
AMAZONAS
ACRE
SAMUEL DAM
RONDÔNIA
MATO GROSSO
TOCANTINS
GOIÁS
FORMER LIMIT OF LEGAL AMAZON
LEGEND
LEGAL AMAZON
STATE
CITY OR OTHER LOCATION
DESTRUCTIVE SAMPLE SITE
DAM
PLANNED DAM
0 125 250
Km

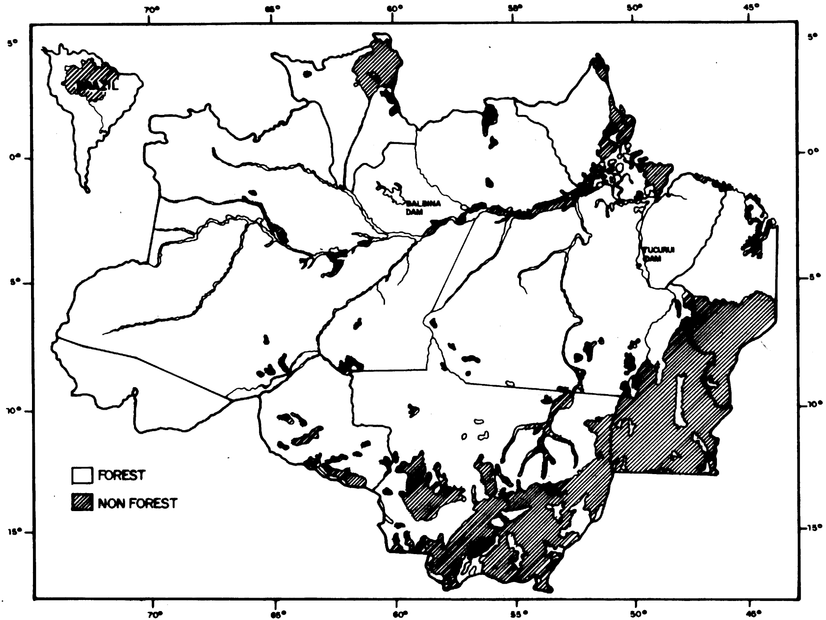

70°
65°
60°
55°
50°
45°
5°
0°
5°
10°
15°
BRAZIL
BALBINA DAM
TUCURUI DAM
FOREST
NON FOREST

TABLE 2: FOREST VEGETATION TYPES IN THE BRAZILIAN LEGAL AMAZON

Cate-gory	Code	Group	Subgroup	Class
Dense Forest	Da-0	Ombrophilous forest	Dense forest	Alluvial Amazonian
	Db-0	Ombrophilous forest	Dense forest	Lowland Amazonian
	Dm-0	Ombrophilous forest	Dense forest	Montane Amazonian
	Ds-0	Ombrophilous forest	Dense forest	Submontane Amazonian
Non-dense forest	Aa-0	Ombrophilous forest	Open	Alluvial
	Ab-0	Ombrophilous forest	Open	Lowland
	As-0	Ombrophilous forest	Open	Submontane
	Cs-0	Seasonal forest	Deciduous	Submontane
	Fa-0	Seasonal forest	Semideciduous	Alluvial
	Fs-0	Seasonal forest	Semideciduous	Submontane
	La-0	Woody oligotrophic vegetation of swampy and sandy areas		Open 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 [ecotones]		Woody oligotrophic vegetation of Swampy and sandy areas--ombrophilous forest
	ON-0	Areas of ecological tension and contact [ecotones]		Ombrophilous forest--seasonal forest
	Pf-0	Areas of pioneer formations [early succession]		Fluvio-marine influence
	SM-0	Areas of ecological tension and contact [ecotones]		Savanna--dense ombrophilous forest
	SN-0	Areas of ecological tension and contact [ecotones]		Savanna--seasonal forest
	SO-0	Areas of ecological tension and contact [ecotones]		Savanna--ombrophilous forest

TABLE 3: AREA ORIGINALLY PRESENT IN EACH FOREST ECOREGION IN THE BRAZILIAN LEGAL AMAZON (10^6 t)

Category	Code	Acre	Amapa	Amazonas	Maranhao	Mato Grosso
Dense forest	Da-0		9,011	164,876		
	Db-0	16,408	2,184	615,203	22,586	
	Dm-0		113	10,181		
	Ds-0	518	99,220	178,103	1,988	23,154
	Subtotal	16,926	110,528	968,363	24,574	23,154
Non-dense forest	Aa-0	10,591		65,748		
	Ab-0	114,380		211,052		
	As-0			37,555		124,620
	Cs-0				3,666	736
	Fa-0					3,554
	Fs-0					24,317
	La-0			14,979		
	Ld-0			37,405		
	Lg-0			9,663		
	LO-0			172,607		
	ON-0					168,069
	Pf-0		1,823		2,089	
	SM-0				384	
	SN-0			1,082	6,570	142,778
	SO-0		4,226	27,350		22,124
	Subtotal	124,971	6,049	577,441	12,709	486,198
	Total all forests	141,897	116,577	1,545,804	37,283	509,352

(Table 3, pt 2)

Para	Rondonia	Roraima	Tocantins/ Goias	Total
76,570	2,704	3,326	2,610	259,097
164,091	2,066	10,248		832,786
3,418		20,661		34,373
413,345	14,607	83,692	3,055	817,682
657,424	19,377	117,927	5,665	1,943,938
805	2,273			79,417
	41,064			366,496
286,271	77,794	8,430	1,216	535,886
5,386			115	9,903
				3,554
	7,718	1,041	1,328	34,404
		970		15,949
		10,967		48,372
		9,767		19,430
		30,184		202,791
2,991	4,801	3,045		178,906
3,894				7,806
				384
27,812	4,781	904	14,465	198,392
59,734	21,932	4,286	6,551	146,203
386,893	160,363	69,594	23,675	1,847,893
1,044,317	179,740	187,521	29,340	3,791,831

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 "vegetation zones," there are a total of 111 vegetation zones in the Legal Amazon, of which 78 are "forest."

Forest volumes

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 (Brazil, Projeto RADAMBRASIL, 1973-1983) and one by the Food and Agriculture Organization of the United Nations (FAO) in the 1950s (Glerum, 1960; Heinsdijk, 1957, 1958a,b,c). A total of 2954 ha of usable data has been extracted from these studies for vegetation types classified as forest. Almost 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 of 25-cm DBH. Almost all of the FAO and RADAMBRASIL 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 IBGE/IBDF (IBAMA) map used here (Table 2). The RADAMBRASIL and FAO vegetation classifications were translated to the IBAMA code, and data with unresolved inconsistencies were discarded.

Deriving biomass estimates from forest volume data

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 4. It should be noted that these parameters lead to estimated biomass values substantially higher than those derived by Brown and Lugo (1992a) 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 10-cm DBH, dead biomass and below-ground biomass (see Fearnside, 1992, 1993c). All of these components must be added to the estimates for use in estimating carbon stocks for greenhouse gas calculations.

(Table 4 here)

TABLE 4: PARAMETERS FOR DERIVING BIOMASS ESTIMATES FROM RADAMBRASIL AND FAO FOREST VOLUME DATA

Factor	Multiplier
Calculation of stemwood volume for trees of DBH >10 cm:	
Volume expansion factor (30-10 cm DBH) (RADAMBRASIL)	1.25
Volume expansion factor (25-10 cm DBH) (FAO)	1.22
Conversion of stemwood volume to biomass:	
Wood density (basic specific gravity)	0.69
Biomass expansion factor	note a
Adjustments to above-ground live biomass (b):	
Hollow trees	0.9077
Vines	1.0425
Other non-tree components	1.0021
Palms	1.0350
Trees <10 cm DBH	1.1200
Trees 30-31.8 cm DBH	1.0360
Bark (volume & density)	0.9907
Sapwood (volume & density)	0.9948
Form factor	1.1560
Adjustments for other components (b):	
Dead above-ground biomass:	1.0860
Below-ground:	1.2914

(a) Biomass expansion factor (BEF) from Brown and Lugo 1992: BEF = Exp (3.213-(0.506 ln (SB))) for SB <190 t/ha; 1.74 for SB >190 t/ha, where SB = stand biomass in t/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 >10cm DBH is in trees >30 cm DBH. Non-dense forest = 1.50 (67% of volume >30 cm DBH).

(d) 21 1-ha plots in Para 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, pers. comm. 1991.

(g) Fearnside et al. nd-b, nd-c; 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. N.B.: a lower contribution from this factor has been found in French Guiana, where 2.38% of above-ground biomass is in trees of DBH <10 cm (Lescure et al. 1983: 245).

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

(l) Density: D.A. da Silva, pers. comm. 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 4, pt. 2)

Source	Note on basis
Brown and Lugo 1992a	c
Brown and Lugo 1992a	
Fearnside unpublished manuscript	d
Brown and Lugo 1992	e
Fearnside 1992	f
Fearnside 1992	g
Fearnside 1992	h
Fearnside 1992	i
Fearnside 1992	j
Fearnside 1992	k
Fearnside unpublished manuscript	l
Fearnside unpublished manuscript	m
Fearnside 1992	n
Table 5	o
Table 6	p

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 from direct measurements are presented in Table 5. Below-ground biomass is derived from the few available studies presented in Table 6. The below-ground component includes underground boles (the taproots directly under the trees) and roots below 1-m depth, based on preliminary data by D. Nepstad (personal communication, 1993). Previous values for below-ground biomass have been underestimates because virtually all available measurements have been restricted to pits dug between the trees, usually to a depth of 1 m.

(Tables 5 and 6 here)

TABLE 5: DIRECT MEASUREMENTS OF FOREST BIOMASS AND COMPONENTS

CATEGORY: Location	State	Forest description	Dry weight of component (t/ha) Above-ground live biomass	Bark
DENSE FORESTS:				
Altamira	Para	Dense upland		
Babaquara Dam	Para	Dense riparian	297.38	19.55
Babaquara Dam	Para	Dense upland	198.27	9.08
Belo Monte Dam (a)	Para	Dense riparian	186.1	11.76
Fazenda Dimona	Amazonas	Dense upland		
Fazenda Dimona	Amazonas	Dense upland		
Reserva Egler	Amazonas	Dense upland	357	
Samuel Dam	Rondonia	Dense upland	387.86	44.24
Samuel Dam	Rondonia	Open submontane	303	
MEAN FOR ALL DATA (k):			288.27	21.16
MEAN FOR COMPLETE DATA (k):			288.27	
NON-DENSE FORESTS:				
Belo Monte Dam (a)	Para	Open upland	126.05	6.45
Samuel Dam	Rondonia	<u>Mata de baixio</u> (open upland forest on poorly drained terrain)	362.45	16.48

(a) Formerly called Kararao Dam.
(b) P.M. Fearnside, P.M.L.A. Graça and F.J.A. Rodrigues unpublished manuscript.
(c) Revilla Cardenas 1988: 76.

(d) Revilla Cardenas 1988: 77.
(e) Revilla Cardenas 1987: 51.
(f) Fearnside et al. 1993.
(g) P.M. Fearnside, P.M.L.A. Graça, N. Leal Filho, F.J.A. Rodrigues and J.M. Robinson unpublished manuscript.
(h) Klinge et al. 1975.
(i) Revilla Cardenas 1986: 39.
(j) Martinelli et al. 1988: 35.
(k) Simple mean of absolute quantities; weighted mean of percentages.
(l) Revilla Cardenas 1987: 54.
(m) Revilla Cardenas 1986: 39.

(Table 5, pt. 2)

Vines	Root mat	Under-story (wood + leaves)	Dead wood	Litter	Total dead (wood + litter)
32.21					
9.74	4.01	9.58	12.32	10.5	22.82
9.02	1.34	9.15	8.87	12.31	21.18
2.81	3.34	5.55	11.17	8.29	19.46
8.1					
10.8					
21.85			25.8	7.2	33.00
4.59	1.96	12.96	1.68	13.56	15.24
			27	10	37
12.39	2.66	9.31	14.47	10.31	24.78
			14.47	10.31	24.78
2.87	3.55	5.99	7.46	9.53	16.99
10.77	10.6	2.59	5.52	5.35	10.87

(Table 5, pt 3)

Percent of above-ground live dry weight (%)

Bark	Vines	Root mat	Under-story	Dead wood	Litter	Total dead
6.57	3.28	1.35	3.22	4.14	3.53	7.67
4.58	4.55	0.68	4.61	4.47	6.21	10.68
6.32	1.51	1.79	2.98	6.00	4.45	10.46
	6.12			7.23	2.02	9.24
11.41	1.18	0.51	3.34	0.43	3.50	3.93
				8.91	3.30	12
7.91	2.45	1.00	3.48	5.02	3.58	8.60
5.12	2.28	2.82	4.75	5.92	7.56	13.48
4.55	2.97	2.92	0.71	1.52	1.48	3.00

(Table 5, pt. 4)

Total above-ground dry weight (t/ha)	Vines as percent of total above-ground	Area of direct survey (m^2)	Source
282.9	11.38	900	(b)
320.2	3.04	2,500	(c)
219.5	4.11	1,875	(d)
205.6	1.37	625	(e)
374.4	2.16	600	(f)
264.6	4.08	360	(g)
390	5.60	2,000	(h)
403.1	1.14	625	(i)
340			(j)
350.0	3.73		
143.04	2.01	625	(l)
373.32	2.88		(m)

TABLE 6: BELOW-GROUND BIOMASS IN AMAZONIAN FORESTS (a)

Location	Above-ground live (t/ha)	Above-ground total	Below-ground between-tree biomass (t/ha)	Below-ground bole and deep root biomass (t/ha) (b)
Manaus, Amazonas	*357*	*390*	*122.5*	74
Jari, Para	*368.91*	*393.24*	*56.96*	34
Paragominas, Para	*336*	*378*	*45*	23
Mean	354	387	75	45

(a) Values in italics are as reported by cited authors; other values are calculated.

(b) Below-ground bole calculated as 50% and roots below 1-m depth as 10% in relation to between-tree estimates to 1-m depth. This is based on preliminary results from Paragominas and Porto Trombetas, Para (D. Nepstad, pers. comm. 1993).

(c) Klinge et al. 1975; Klinge and Rodrigues 1973.

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

(e) Uhl et al. (1988: 670) for above-ground components except above-ground roots (30 t/ha) (D. Nepstad, pers. comm. 1991 cited by I.F. Brown et al. 1992); below-ground between-tree biomass from D. Nepstad (pers. comm. 1994). This refers to between-tree roots to 9-m depth (other between-tree estimates are to 1 m). The value calculated for "below-ground boles and deep roots" given for Paragominas refers only to below-ground boles. The Paragominas estimate, like the other estimates, ignores the below-ground boles directly under the trees: only the roots projecting laterally into the soil from each tree are sampled (D. Nepstad, pers. comm. 1992).

(Table 6, pt. 2)

Approximate below-ground total biomass (t/ha)	Total biomass (t/ha)	Root/shoot ratio (live + dead)	Below-ground percent of total	Below-ground percent of live	Source
196	586	0.50	33.4	35.4	(c)
91	484	0.23	18.8	19.8	(d)
68	446	0.18	15.2	16.7	(e)
120	505	0.31	23.7	25.3	

The total biomass is derived for each of the approximately 3000 samples, and the average for each vegetation zone is calculated. Sample sizes in hectares are given in Table 7. Of the 78 forested vegetation zones appearing on the IBAMA (IBGE/IBDF, 1988) map, 44 (56%) have forest volume data available in the RADAMBRASIL or FAO datasets, and 34 (44%) do not. Fortunately, most of the vegetation zones without data are of relatively minor importance from the standpoint of current greenhouse gas emissions. Of estimated biomass cleared in 1990, they total only 21.5%. Of this, over half is represented by only three vegetation zones: open submontane ombrophilous forest (As-0) in Mato Grosso, the same forest type (As-0) in Rondônia, and the ecotone between savanna and seasonal forest (SN-0) in Tocantins. For the vegetation zones 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 5 of the 19 forest types, no measurement exists for any state. Ten of the 36 vegetation zones without data fall into this category. All of these are in the nondense forest category, and, fortunately, none represents a major vegetation zone from an emissions standpoint. The mean for sampled areas in nondense forests was used as a substitute for these 10 values. Vegetation types with no sample in any state represent only 1.0% of the estimated biomass cleared in 1990; of this small amount, 73.4% is in one vegetation type (mangroves: Pf-0). The mean biomass per hectare in each of the forested vegetation zones, including the values substituted as described above, are presented in Table 8. It is evident that significant variation exists among states and among forest types.

(Tables 7 and 8 here)

TABLE 7: SURVEYED AREA OF ECOREGIONS IN THE BRAZILIAN LEGAL AMAZON (HA WITH COMPLETE DATA)

Category	Code (a)	Acre	Amapa	Amazonas	Maranhao	Mato Grosso (b)
Dense forest	Da-0			1	249	4
	Db-0	11	6	363	18	
	Dm-0		0	2		
	Ds-0	12	30	174		0 51
Subtotal		23	37	788	18	55
Non-dense forest	Aa-0	12		26		
	Ab-0	27		53		
	As-0			8		0
	Cs-0				0	1
	Fa-0					7
	Fs-0					22
	La-0			0		
	Ld-0			0		
	Lg-0			0		
	LO-0			219		
	ON-0					101
	Pf-0		0		0	
	SM-0				0	
	SN-0			2	0	66
	SO-0		0	2		13
Subtotal		39	0	310	0	210
Total all forests		62	37	1,098	18	265

(a) Vegetation codes as defined in Table 2.

1 (b) One ecoregion (Da-0 in Mato Grosso) appears on the 1:1,000,000 scale RADAMBRASIL map.

(Table 7, pt 2)

Para	Rondonia	Roraima	Tocantins/ Goias	Total
17	5	6	0	282
1,028	0	10		1,436
0		25		27
164	0	47	4	482
1,209	5	88	4	2,227
0	0			38
	12			92
86	0	0	0	94
0			0	1
				7
	9	0	0	31
		0		0
		0		0
		0		0
		2		221
0	11	20		132
0				0
				0
2	0	2	0	72
24	0	0	0	39
112	32	24	0	727
1,321	37	112	4	2,954

TABLE 8: FOREST BIOMASS PER HECTARE: MEANS BY ECOREGION, VEGETATION TYPE AND STATE (t/ha) (a)

Category	Code	Acre	Amapa	Amazonas	Maranhao	Mato Grosso
Dense forest	Da-0		442	480		285
	Db-0	411	545	439	430	
	Dm-0		413	324		
	Ds-0	367	574	448	403	377
	Dense forests	409	562	447	428	377
Non-dense forest	Aa-0	398		407		
	Ab-0	427		437		
	As-0			475		350
	Cs-0				360	360
	Fa-0					347
	Fs-0					378
	La-0			408		
	Ld-0			408		
	Lg-0			408		
	LO-0			468		
	ON-0					360
	Pf-0		408		408	
	SM-0				408	
	SN-0			383	361	359
	SO-0		378	545		339
Non-dense forests		424	387	447	370	357
All forests		423	553	447	408	358

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

(Table 8, part 2)

Para	Rondonia	Roraima	Tocantins/ Goias	Mean in sampled plots	Area-weighted mean
387	292	394	466	466	448
548	517	392		517	460
413		420		413	391
486	403	403	104	403	474
489	400	405	271	484	463
501	403			403	407
	378			427	427
338	350	350	350	350	352
360			360	360	360
				347	347
	442	397	397	397	394
		408			408
		408			408
		408			408
		410		468	460
376	511	384		376	365
408					408
					408
449	361	316	361	361	372
385	378	378	378	378	406
355	371	397	367	408	392
440	374	402	349	465	428

Biomass of cerrado

The above biomass calculations apply only to forest. Nonforest areas that are subject to clearing activity can best be assumed to have biomass of *cerrado*. *Cerrado* biomass is derived from firewood volume surveys (Table 9). The mean of the three available *cerrado* firewood estimates corresponds to a total biomass of 45 t/ha.

(Table 9 here)

TABLE 9: CERRADO BIOMASS FROM FIREWOOD VOLUME ESTIMATES

Location	Firewood volume (steres/ha) (a)	Firewood dry weight (t/ha) (b)	Above-ground biomass (t/ha) (c)	Total biomass (t/ha) (d)	Firewood volume reference
Grande Carajas	120	47	52	82	Brazil, PGC/CODEBAR/SUDAM 1986: 70. Estimate for _cerrado_.
Mato Grosso (central part)	25	10	11	17	Brazil, Projeto RADAMBRASIL 1982, Vol. 26: 445. From 54 ha of basal area measurements in Open Arboreal Savanna (_campo cerrado_)
Mato Grosso (southern part)	54	21	24	37	Brazil, Projeto RADAMBRASIL 1982, Vol. 27: 363. From 44 ha of basal area measurements in Open Arboreal Savanna (_campo cerrado_).
Mean	66	26	29	45	

(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 $\geq$ 10 cm diameter.
(d) Assumes underground biomass = 36% of total biomass (value used by Seiler and Crutzen 1980: 212 for "scrubland").

Most of the area of nonforest original vegetation (i.e., prior to recent European settlement) is cerrado, other types occupying relatively small areas. Nine nonforest vegetation types occur in the region according to the 1:5,000,000 scale Brazil, IBGE/IBDF (1988) map (Fearnside and Ferraz, 1995).

DISCUSSION

Considerable confusion has prevailed in using biomass numbers for global warming calculations, often as a result of using data published for a specified portion of the biomass (such as above-ground live biomass) as a measure of total biomass. Table 10 summarizes the relationships between different biomass measures, based on available data from Brazilian Amazonia; this has proved very useful in keeping the relationships between these quantities clear.

(Table 10 here)

TABLE 10: AVERAGE PERCENTAGES OF BIOMASS COMPONENTS, BASED ON AVAILABLE DATA FROM BRAZILIAN AMAZONIA (a)

Relationship	Above-ground				Below-ground	Total live	Total (live + dead)
	Live	Fine litter	Other dead	Total			
Quantity relative to above-ground live biomass:	100.00	3.58	5.02	108.60	33.59	133.59	142.18
Quantity relative to total above-ground biomass:	92.08	3.29	4.62	100.00	30.93	123.01	130.93
Quantity relative to total live biomass:	74.73	2.67	3.75	81.15	25.27	100.00	106.42
Quantity relative to total biomass:	70.22	2.51	3.53	76.26	23.69	93.96	100.00

(a) Based on data in Tables 5 and 6.

The biomass estimate in the present paper refers to total biomass, including below-ground and dead components. This is the most relevant biomass measure for global warming calculations that involve comparison of carbon stocks in forest biomass with those in the biomass of the vegetation that replaces forest.

Even when the confusion of comparing one biomass measure with another is eliminated, the biomass estimate derived in the present paper is higher than other estimates. This is true for a number of reasons. It is higher than the Brown and Lugo (1984) estimate because of the conversion factors used to calculate volume from the original measurements of tree diameters, and to calculate biomass from volume. Brown and Lugo's (1984) estimate was based on Food and Agriculture Organization of the United Nations (FAO) inventories of timber volumes in trees over 25 cm diameter at breast height (DBH). Using the same methodology, calculations from the original data indicate that only 1 of 16 localities has a biomass value as low as Brown and Lugo's (1984) mean value of 155.1 t/ha (Fearnside, 1986, 1987).

The present estimate is higher than the S. Brown et al. (1989) estimate because of a number of needed corrections, of which form factor is the largest (Table 4). S. Brown et al. (1989) revised their previous (Brown and Lugo, 1984) biomass values upward by 28-47%, mainly as a result of an improved correction for the small diameter biomass components not directly measured in the original FAO surveys of forest volume and as a result of a higher estimate for mean wood density. A substantial further upward adjustment is necessary for factors omitted from the S. Brown et al. (1989) estimate, including roots, palms, vines, stems <10 cm DBH, and dead biomass. S. Brown et al. (1989, p. 898) calculate a mean above-ground live biomass of 169.68 t/ha for undisturbed broadleafed productive forests in Tropical America, which is equivalent to 223 t/ha of total live biomass if a conversion factor of 1.32 is applied (from Table 10, based on studies reviewed in Fearnside et al., 1993), or 197 t/ha if calculated with the factor of 1.16 used by S. Brown et al. (1989, p. 898). Inclusion of dead biomass would raise the total from 223 to 237 t/ha (based on Table 10). Applications of the S. Brown et al. (1989) estimate to global carbon calculations (e.g., Houghton, 1989, 1991) have not included adjustments for the omitted biomass fractions (Table 10), which, taken together with adjustments for form factor and other considerations (Table 4), increase the total biomass present by about 71%. On the other hand, it should be noted that the effect is offset in these particular calculations because they used an estimate of deforestation (Myers, 1989, 1990, 1991) that overestimates the rate in Brazil by a factor of two (see Fearnside, 1990).

Brown and Lugo (1992a) derived an estimate of 162 t/ha, subsequently revised to 227 t/ha (Brown and Lugo, 1992b), as the average above-ground live biomass of dense forests in Brazilian Amazonia, based on forest volume data from RADAMBRASIL Project inventories (Brazil, Projeto RADAMBRASIL, 1973-1983). A variety of factors not considered by Brown and Lugo indicate the need for upward adjustment of this estimate (Fearnside, 1992; see Brown and Lugo, 1992c, Fearnside, 1993c). On the other side, Sombroek (1992) believes that Brown and Lugo's (1992a) estimate should be scaled down because of nonforest vegetation types excluded from the RADAMBRASIL surveys and because the survey teams' choices of plot locations within the sampled vegetation may have avoided patches with low biomass. The exclusion of nonforest vegetation is not relevant to biomass estimates confined to forest (as opposed to the full 5×10^6 km^2 Legal Amazon region of Brazil). Any bias in the choice of sample plots, however, would indeed affect Brown and Lugo's results as well as others based on RADAMBRASIL survey data, including those in the present paper.

The effect of logging is particularly important in interpreting forest biomass estimates in terms of the contribution of deforestation to global warming. The estimates presented here reflect the biomass present at the time of the forest inventories, which were done before much of the recent logging activity in the region. While clearing in the 1970s usually involved burning felled forest from which no timber had been removed, subsequent improvements in road access and increases in timber prices have made it commonplace in the 1990s for any salable timber to be removed prior to clearing. The appropriate biomass figure to use in emission calculations--pre-logging or post-logging biomass--will depend on the nature of the calculations. The post-logging biomass should be used only if logging is explicitly included in the calculations. Lugo and Brown (1992) are emphatic in condemning the use of biomass estimates for undisturbed forests when emissions calculations are done for deforestation. However, it should be pointed out that explicit treatment of logging is currently rare in such calculations, and that a greater bias occurs if a reduced "post-logging" biomass is used in calculations that omit explicit emissions estimates for logging.

In using biomass estimates for greenhouse gas emissions calculations, one must be careful to avoid double counting of carbon affected by logging. This would occur if pre-logging forest biomass were used in a calculation that computes carbon releases through logging when the same value for biomass is used for deforestation emissions, thereby counting the same carbon both when forests are cleared and when the products of logging decay.

The present estimate is higher than this author's previous estimates (Fearnside, 1991, 1992) because of better data for biomass in the southern portion of the region where deforestation activity is concentrated. The previous estimates had used statements by foresters in Mato Grosso regarding timber volumes in that very important state, whereas the present estimate uses data from the RADAMBRASIL survey for Mato Grosso. None of Brown and Lugo's estimates contains any data from Mato Grosso. The Mato Grosso data in the present paper are especially important for estimates of greenhouse gas emissions from deforestation, as this state accounted for 28% of the forest clearing activity in the Legal Amazon region in 1990, and 26% in 1991 (P.M. Fearnside, L.G. Meira Filho, and A.T. Tardin, unpublished manuscript; Fearnside, 1993b).

The region-wide mean derived here (428 t/ha) refers to pre-logging total biomass in all original vegetation defined as forest (3.8×10^6 km^2) in the Legal Amazon. Because both the deforestation rate and the average biomass present vary among states, estimates of emissions from deforestation must use biomass values that are weighted by the rate of clearing. Adjustments for logging appropriate to the emissions estimate must also be made.

CONCLUSIONS

Analysis of published wood volume data from 2954 ha of forest inventory surveys distributed throughout the region permit more reliable estimates of average biomass in Amazonian forests than was previously possible. Average total biomass (including dead and below-ground components) in unlogged original forests present in the Brazilian Legal Amazon is estimated to be 428 t/ha. The average above-ground biomass is 327 t/ha, of which 301 t/ha is alive; below-ground biomass averages 101 t/ha. Disaggregating the total biomass estimates by state and forest type allows the data to be used in conjunction with Brazil's LANDSAT-based deforestation estimates, which are reported on a state-by-state basis.

NOTES

(1) 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 zigzagging along the 13th parallel S latitude, which has been the limit of

the Legal Amazon in this area since 1953. Different government agencies now use different definitions of the Legal Amazon. The National Institute for Space Research (INPE), which interprets satellite imagery for deforestation, considers the present state of Tocantins to define the limit of the Legal Amazon here. Deforestation data from previous years have been reinterpreted 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^o S latitude, and 7411 km^2 of Tocantins lies south of this parallel. Virtually none of the portion of Tocantins south of 13^o S was originally forested.

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FIGURE LEGENDS

Fig. 1. Biomass controversy: estimates for unlogged forests in Brazilian Amazonia by Brown and Lugo (open squares) and by Fearnside (solid triangles).

Fig. 2. Brazil's Legal Amazon region, with locations mentioned in the text.

Fig. 3. Forest and nonforest in the Brazilian Legal Amazon (Source: Fearnside and Ferraz, 1995).